Steve Geer
22nd July, 1999

MUCOOL
Ionization Cooling R&D

- MUCOOL Goals & History
- Ongoing R&D
- Beam Test Goals
- Beamline
- Instrumentation
- Timeline & Costs
- Summary & Needs

---

http://www.fnal.gov/projects/muon_collider/cool/cool.html
http://www-mucool.fnal.gov/notes/notes.html

The MUCOOL Collaboration

~70 Physicists from 16 Institutions

Fermi National Laboratory
Rockefeller University
Jefferson Laboratory, Newport News, VA
Lawrence Berkeley National Laboratory
Univ. of California Los Angeles
University of Mississippi
Brookhaven National Laboratory
KEK High Energy Research Organization, Japan
Argonne National Laboratory
Princeton University
University of Iowa
Budker Institute of Nuclear Physics, Novosibirsk
Fairfield University
Univ. of California Berkeley
Illinois Institute of Technology
Indiana University

http://www.fnal.gov/projects/muon_collider/cool.html

http://www−mucool.fnal.gov/notes/notes.html

April 15, 1998

Proposal P904

Ionization Cooling Research and Development Program for a High Luminosity Muon Collider

Abstract

We propose a six−year research and development program to develop the hardware needed for ionization cooling, and demonstrate the feasibility of using the ionization cooling technique to produce cooled beams of positive and negative muons for a muon collider. We propose to design and prototype critical sections of the muon ionization cooling channel. These sections would be tested by measuring their performance when exposed to single incoming muons with momenta in the range 100 − 300 MeV/c. The phase−space volume occupied by the population of muons upstream and downstream of the cooling sections would be measured sufficiently well to enable cooling to be demonstrated, the calculations used to design the cooling system tested, and optimization of the cooling hardware to be studied.

MUCOOL Mission

- A high−luminosity muon collider requires a muon cooling system that can reduce the 6−D phase−space occupied by the"cloud" of muons coming from a pion decay channel by a factor of $10^5 - 10^6$.

- Short cooling time ($\tau_\mu = 2\mu s$) −> new cooling method −> Ionization Cooling.

- Our concept of an ionization cooling channel can be thought of as a long Linac filled with material. Keeping the bunch in tact whilst cooling it by a large factor is a real challenge involving many important technical details.

- We believe that the feasibility of a practical cooling channel can only be demonstrated by building & testing one or more cooling sections.

The mission of the MUCOOL collaboration is to develop, prototype, and test all of the critical components needed for a muon cooling channel, and ultimately to build short cooling sections & test them in an appropriate low energy muon beam.

Strategy

- Up to now we have focussed our efforts on a late transverse cooling section of an ionization cooling channel:

- This choice makes sense if we:

1. Assume that we will arrive at a solution for the emittance exchange sections.
2. Want to address the question: Can we achieve the final emittances needed for a muon collider ?

- Recently there has been growing interest in the possibility of building a muon storage ring neutrino source as a step towards a muon collider –> emphasizes the importance of the first stage of cooling –> a very different MUCOOL R&D program that has not been thought out in detail.

–> Enhances the case for cooling R&D

–> Injects some uncertainty into the R&D plan until we have guidance on where to put the R&D emphasis.

MUCOOL History

- **May 1997: MUCOOL born at the Muon Collider Collaboration meeting, Orcas Island.**
- **August 1997: MUCOOL R&D program presented to Gilman panel.**
- **April 1998: MUCOOL Proposal submitted to Fermilab PAC.**
- **April 1998: First DOE funds for MUCOOL hardware R&D −> $600K for FY98 used primarily to support RF R&D.**
- **May 1998: MUCOOL presentation to FNAL PAC.**
- **June 1998: MUCOOL FY99 presentation to FNAL PAC (Aspen retreat).**
- **FY99: $1,200K DOE funds for MUCOOL activities (out of $2,000K for Muon Collider R&D). MUCOOL funds used for RF R&D plus cooling channel engineering design studies. In addition, $300K from FNAL Base Program funds allocated for Liquid Lithium Lens R&D.**

Ongoing MUCOOL Activities

1. **Develop the high−gradient RF cavities needed towards the end of the cooling channel.**

2. **Develop an RF power source that can drive these cavities.**

3. **Prepare an RF high−power test setup (Lab G) to test the prototype cavities in a solenoid field.**

4. **Design a (15 T) alternating solenoid transverse cooling section corresponding to a cooling stage towards the end of the cooling channel. This includes the RF modules, solenoids, and liquid hydrogen absorbers.**

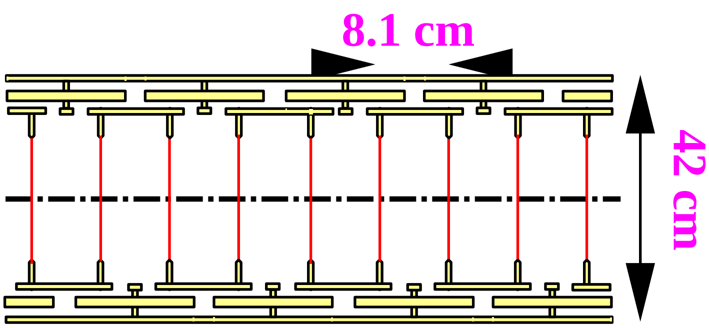
5. **Develop a short (15 cm) liquid lithium lens ... first step towards lenses that could be used at the end of the cooling channel (joint project with FNAL pbar source).**

6. **Design a cooling beam test facility & experiment and prototype instrumentation.**

MUCOOL RF R&D

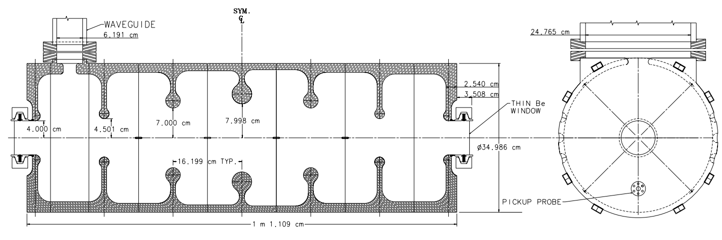
BNL, FNAL, LBNL, Mississippi

Be window cavity design



π/2 805 MHz Interleaved Cavity

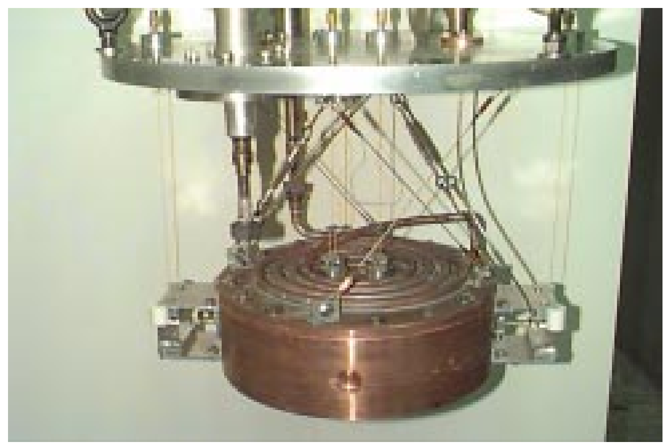
Open cell cavity design



Standing wave linac structure

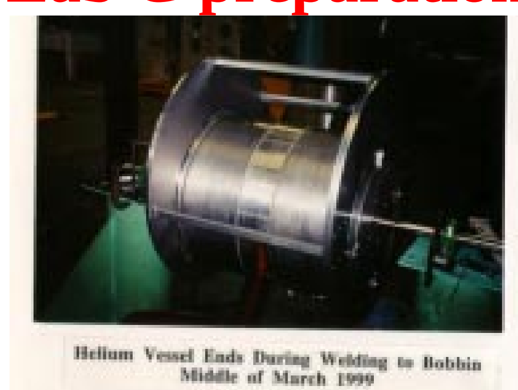
Be window tests

LN_2 Temp Be Properties



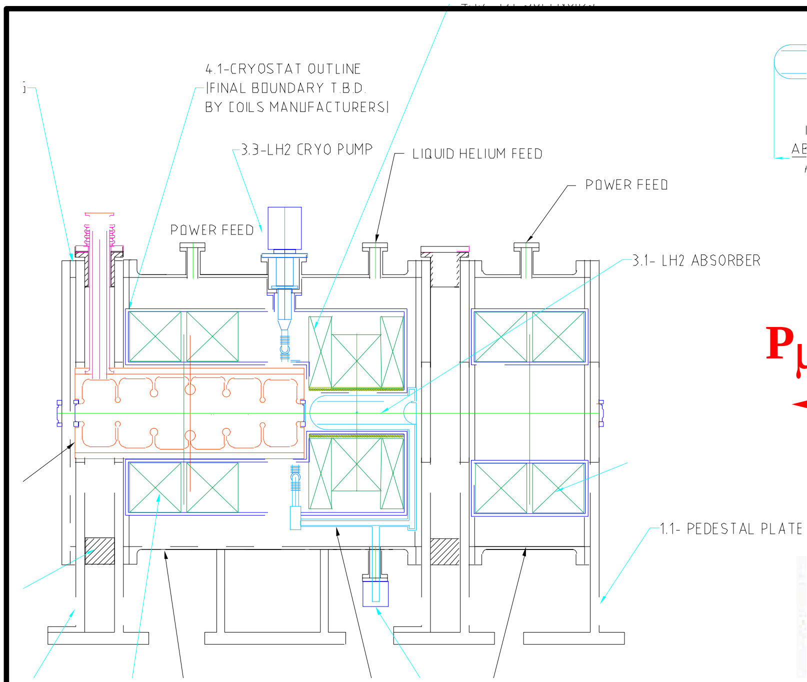
Low power cavity tests

Lab G preparation



Power source development

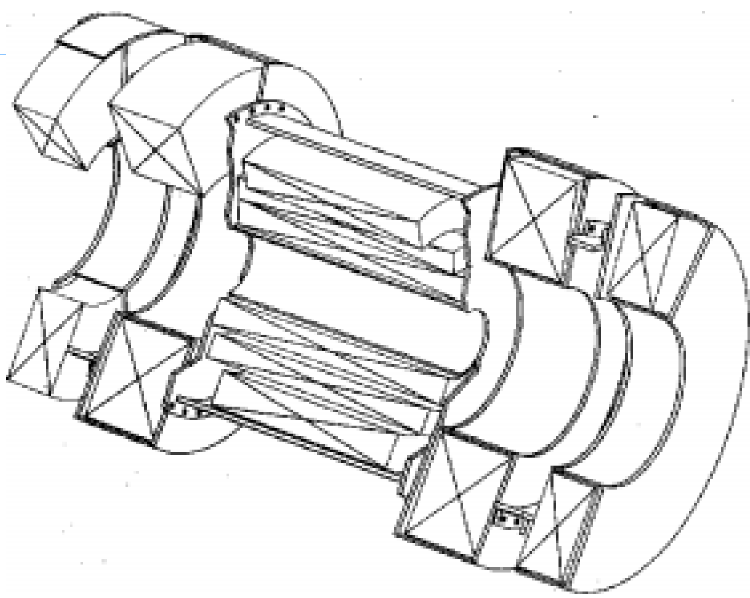
MUCOOL Cooling Section Design



BNL/FNAL/IIT Design

P_μ = 187 MeV/c

- 42 cm Li H_2 absorber
- 15T solenoid, r = 10 cm
- 1 m LINAC

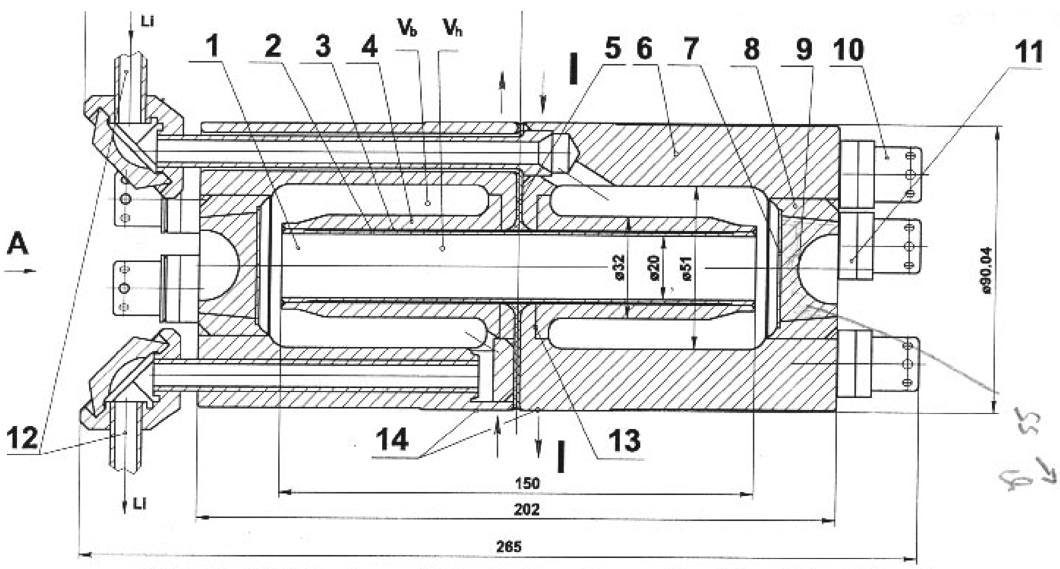


15T Coil Pack: NHMFL

LH_2 Absorber: IIT

MUCOOL/Pbar source Liquid Lithium Lens R&D

- A contract between Novosibirsk and FNAL exists to develop a 15 cm long liquid lithium lens for anti−proton collection (radius = 1 cm, surface field = 13 T, repetition rate = 0.5 Hz).



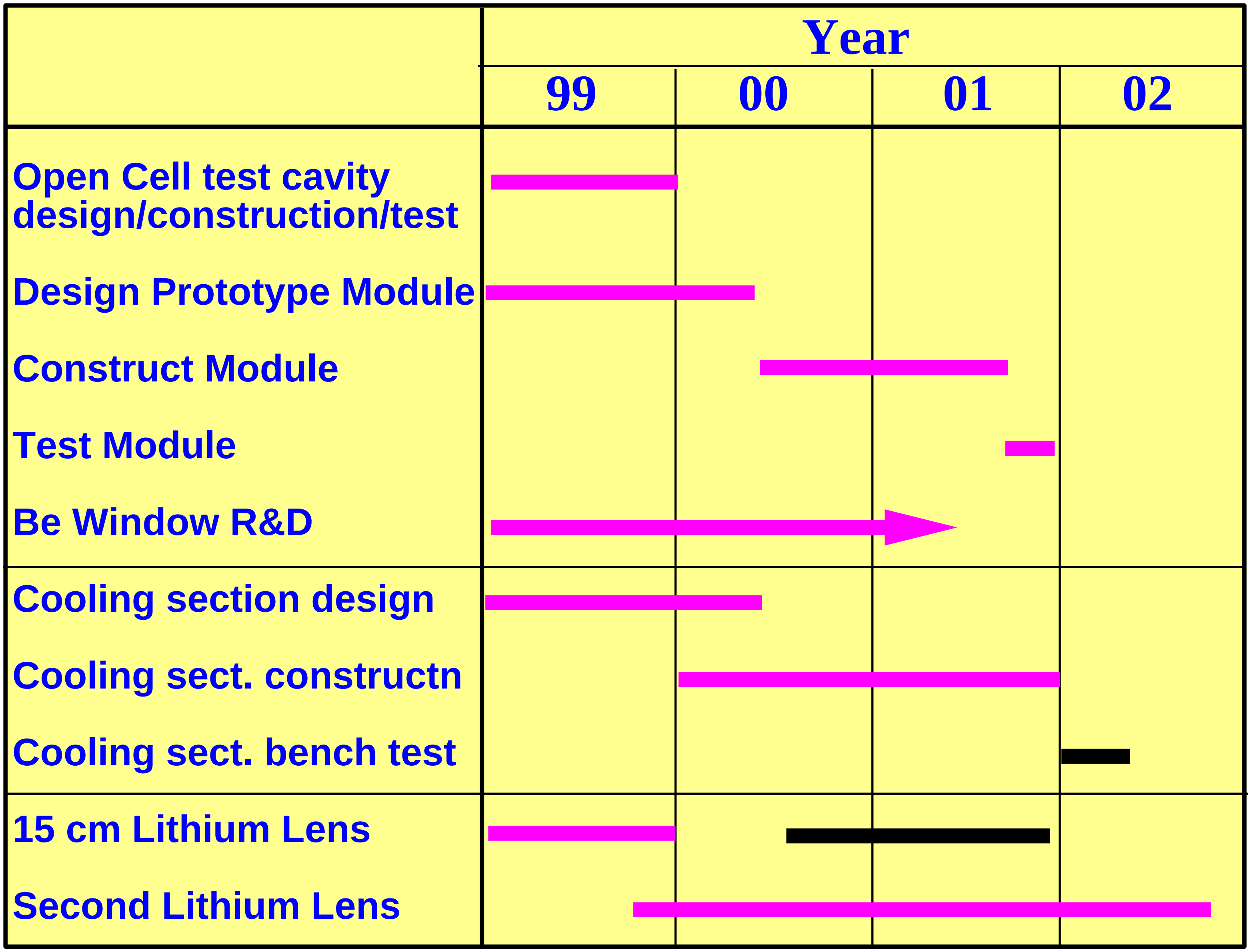
- CY00: Test lens (10^6 pulses) & deliver to FNAL.

	Year			
	99	00	01	02
15 cm Lens constr−uction + BINP tests				
15 cm tests at FNAL				

- Also some prelim. MUCOOL Li lens design studies at ANL.

Near−Term Strawman R&D Plan†

† Contingent upon funding, etc.



By CY02 we will be ready to test a first cooling section in a low energy muon beam.

Cooling Hardware Beam Test

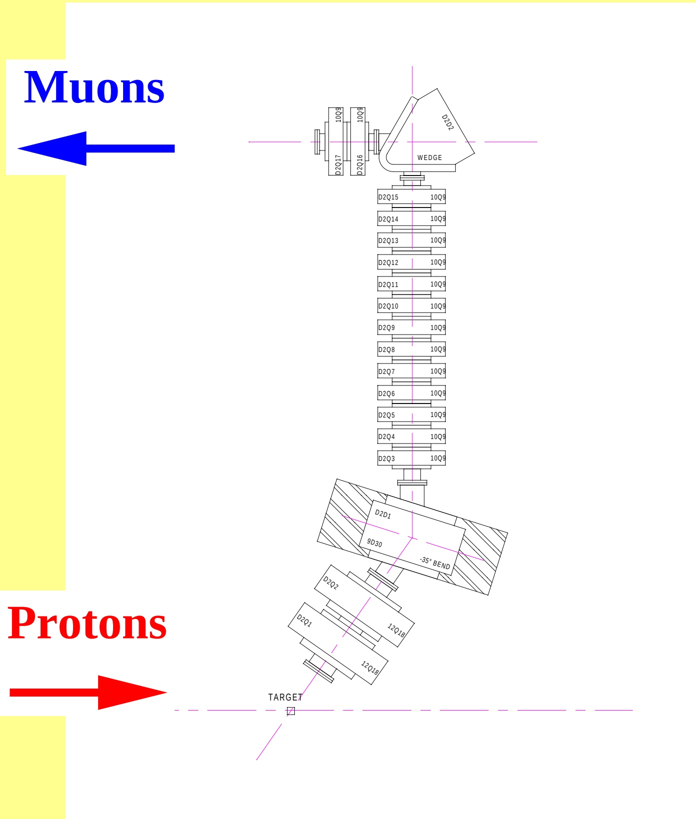
- **After designing, building, & bench testing prototype cooling components, we would like to assemble short cooling sections and measure their performance in a low energy muon beam:**
  - ☞ **Demonstrate cooling capability of prototypes.**
  - ☞ **Test the cooling calculations (= design tools).**
  - ☞ **Study optimization of cooling channel.**
  - ☞ **CLIMB UP THE LEARNING CURVE.**

- **Therefore, if we maintain our near−term R&D schedule, then in CY02 we will need an ionization cooling test facility:**

Muon Beamline + Exptl Area + Instrumentation

- **Single particle experiment: measure the position of muons in 6−D phase−space, before & after the cooling setup, sufficiently well to test the perform− ance of the cooling channel.**

Low Energy Muon Beam



Existing low energy muon beamlines consist of a proton source, pion production target, and large aperture quadrupole decay channel with big bends to suppress backgrounds.

Need :

- P_{beam} = 100 − 300 MeV/c
- $\Delta P/P \sim 5\%$
- Purity > 99% after tagging
- $\varepsilon_{\perp} \sim 1500\,\pi$ mm−mrad

- **Initial beamline design studies based on BNL D2 Quads which are potentially available.**

Q1:	12Q18,	B = 4.65 kG
Q2:	12Q18,	B = 3.88 kG
Q3−Q15:	10Q9,	B = 9.16 kG
Q16:	10Q9,	B = 4.22 kG
Q17:	10Q9,	B = 4.28 kG
Q18:	10Q9,	B = 1.44 kG

- **Large aperture quads from the MEGA beamline (21 Quads with ≥12 inch apertures) at LANL are also potentially available.**

Beamline Design

- Initial studies have been done for a 187 MeV/c muon beam produced using either an FNAL Booster or MI primary proton beam (meson hall), together with the D2 Quads.

Primary beam requirements & Muon rates.

Initial beam study for 187 MeV/c muon beam (*Tom Kobilarchik*):

	MI	Booster
Proton Energy (GeV)	120	8
Protons / spill	5×10^{12}	1×10^{11}
Cu. target length	$1.5\ \lambda$	$0.02\ \lambda$
Muons captured / proton	8.9×10^{-9}	7.9×10^{-12}
Muons / 6μs interval	0.27	0.79
f_{RF}	$2.5 \times 10^{-5(*)}$	0.05
Useful Av. muon rate	0.4 Hz	0.2 Hz

- Using MI protons transported to the meson hall, MUCOOL would take a "ping" of 2×10^9 protons from the 5×10^{12} proton spill. This would be done using a pulsed magnet (τ = 3μs, flat top = 30 μs) which comes to full field within the abort gap within the extracted beam. The unused protons would either be dumped on MTT or used for meson area experiments.

Beamline design status

- **Initial beamline studies suggest that the MUCOOL needs can be provided using primary protons from either the MI or Booster, together with a "conventional" pion decay channel.**

  - Tom Kobilarchik, "Optimization of the D2 Beamlime", MUCOOL Note 3.
  - D. Finley, T. Kobilarchik, N. Holtkamp, M.−J Yang, "Beamline options for the muon cooling experiment" MUCOOL Note 31.

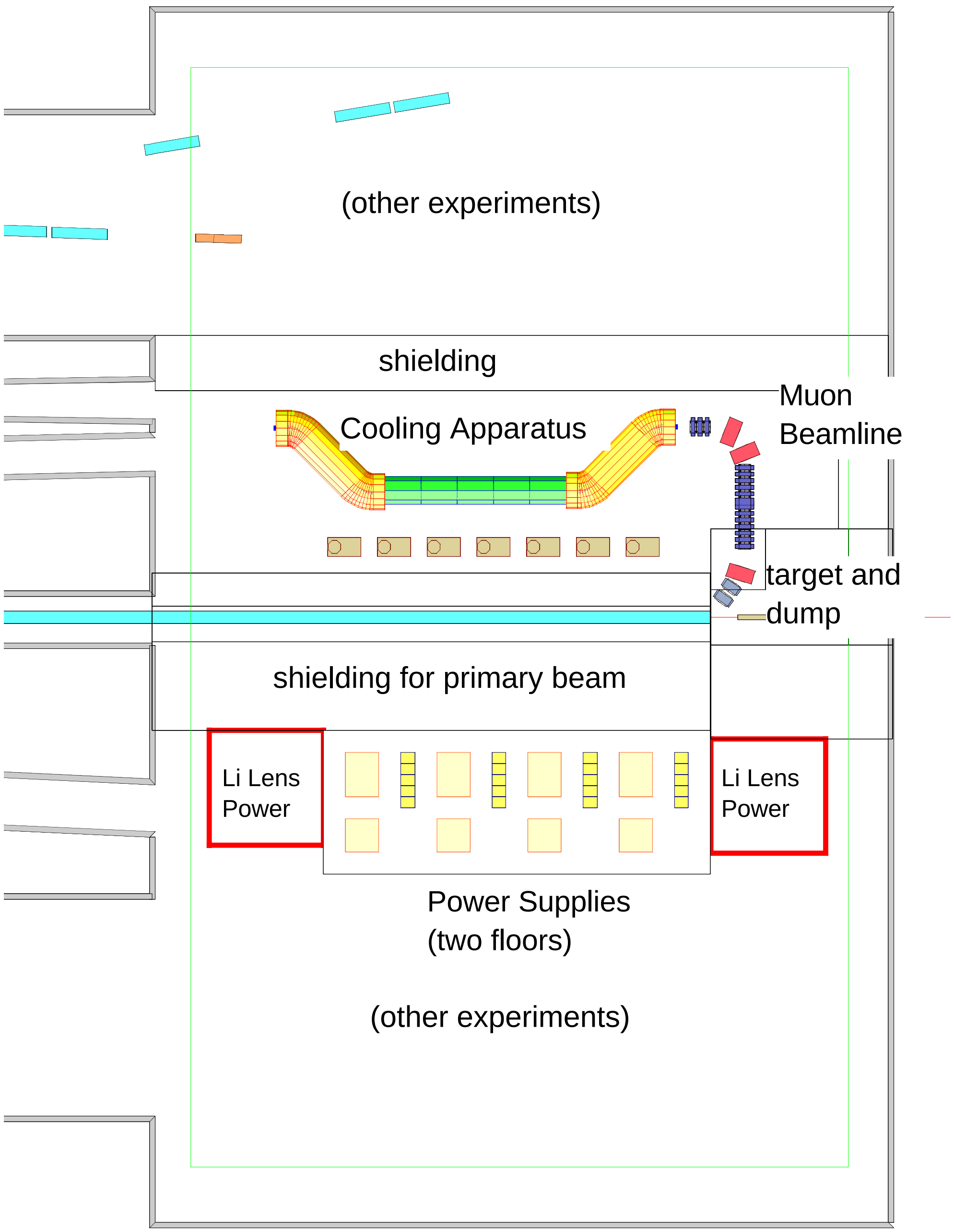
- **Beamline studies need to be completed :**

  - **Momentum selection (100−300 MeV/c) ?**
  - **Bunched beam possibilities −> more later**

−> Beamline design report

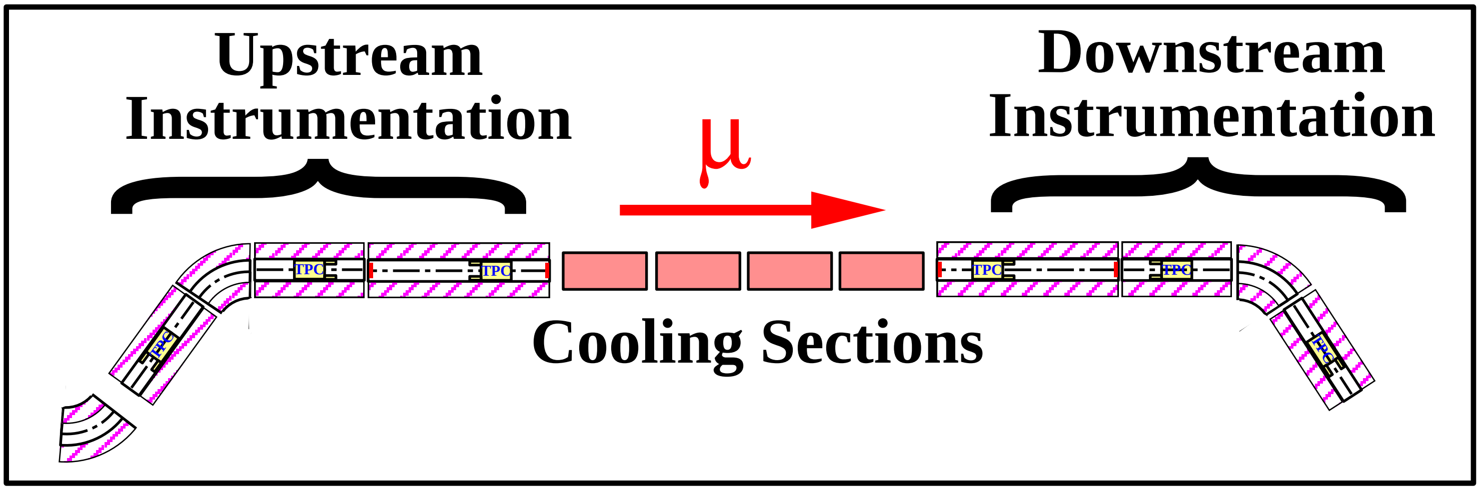
Muon Cooling Beam Test Facility Layout

T. Kobolarchik



Example: The MCenter Beamline

Measurement Requirements



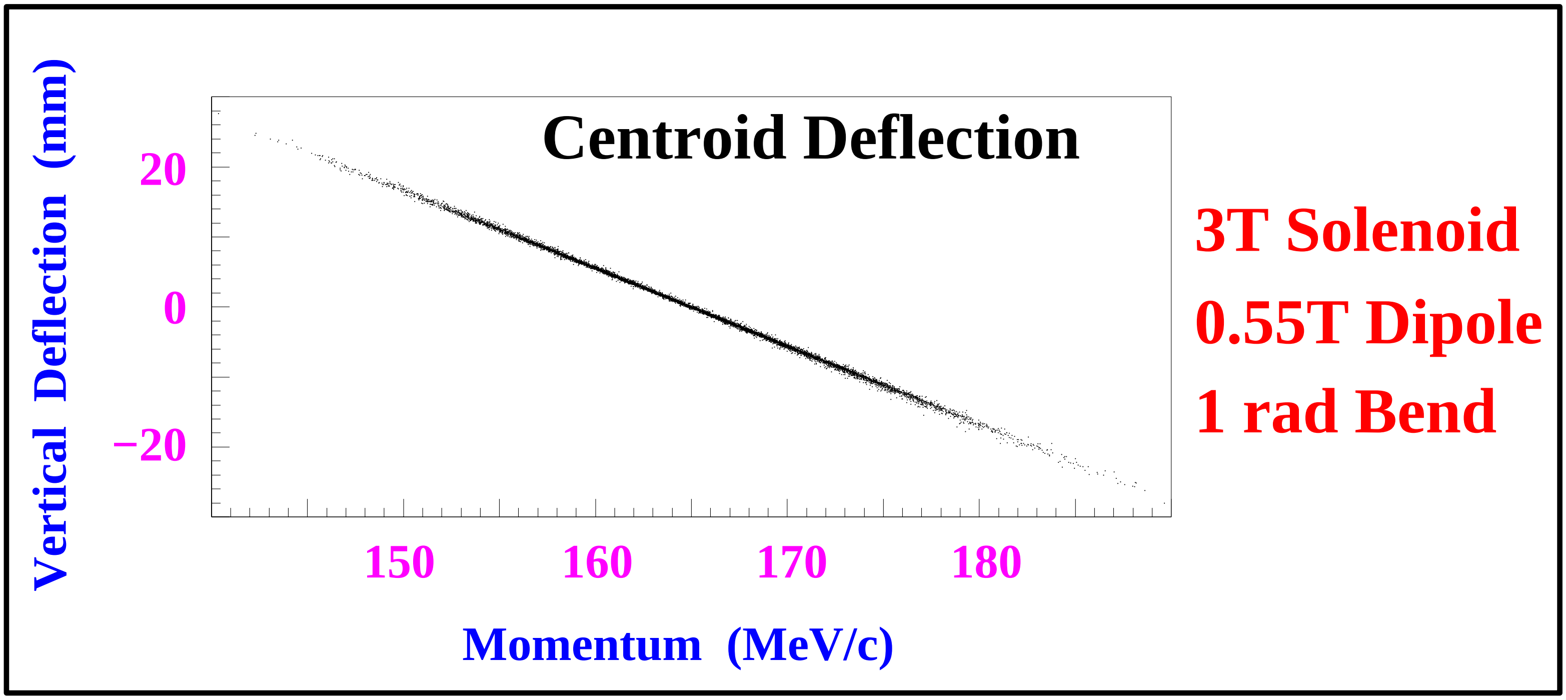
- Measure the non−decay loss of muons (~ 1%) with a precision of 10% −> 10,000 muons per measur−ement within the acceptance of the cooling setup.

- Measure the phase−space volume occupied by the input and output muon populations with a precision of a few %.

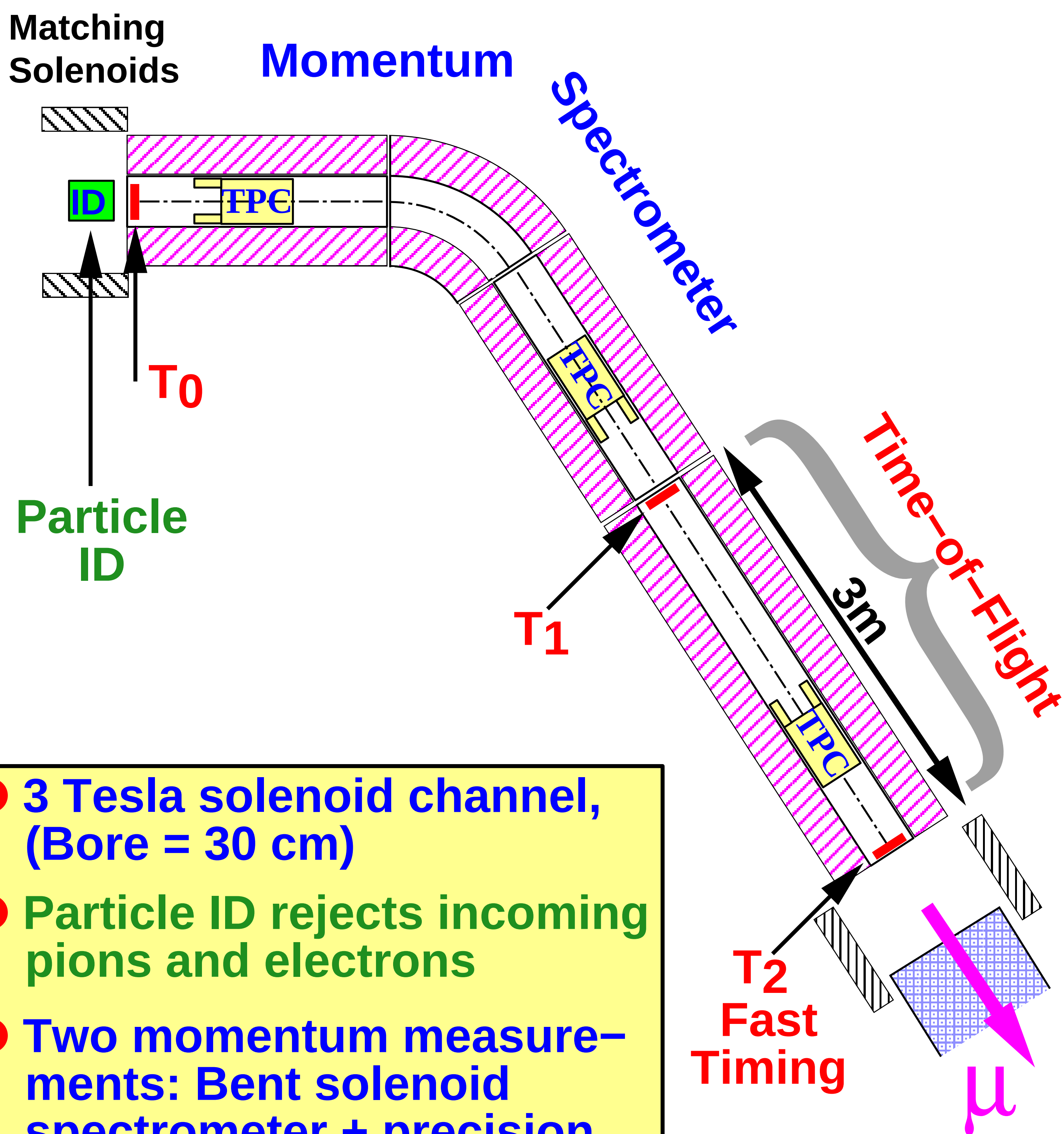
Variable i	Expected input σ_i	Required σ_{D_i}	Required $\delta\sigma_{D_i}$
x	24 mm	200 μm	40 μm
y	24 mm	200 μm	40 μm
x‘	33 mr	5 mr	1 mr
y‘	33 mr	5 mr	1 mr
P	5 MeV/c	0.23 MeV/c	0.05 MeV/c
t	40 ps	8 ps	2 ps

Muon Measuring Systems

- We must measure $(x, y, x^{/}, y^{/}, p, t)$ of the incoming and outgoing muons.
- The large beam phase−space must be confined within the measuring system ... use a solenoid channel.
- We need a momentum spectrometer within the solenoid channel. An elegant way to implement this is to use the curvature drift effect within a bent solenoid embedded in a guiding dipole field:



- **Example:** To measure momentum with a precision of 0.2 MeV/c using a horizontal bend requires the vertical helix deflection to be measured with a precision of 220 μm.

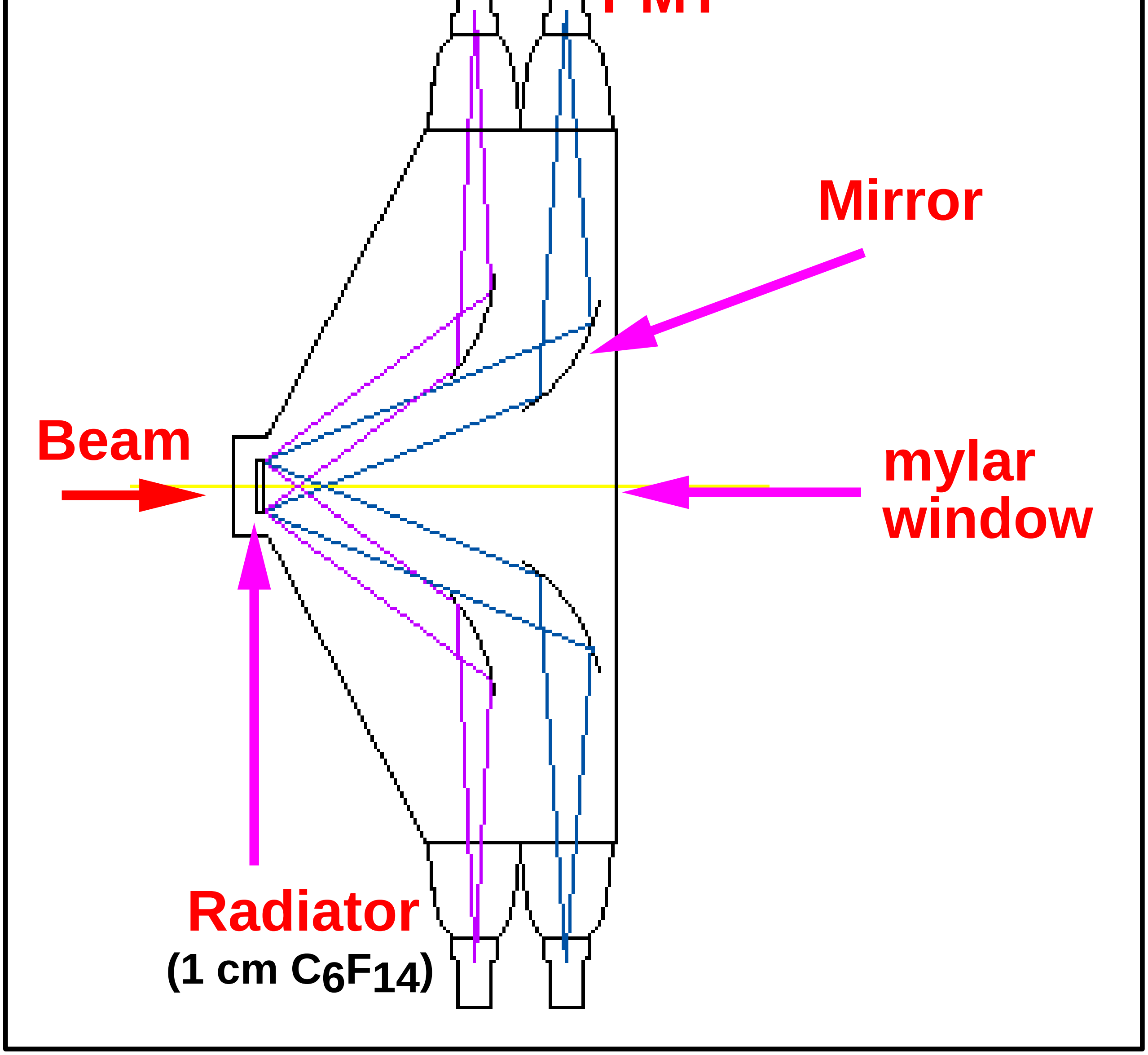


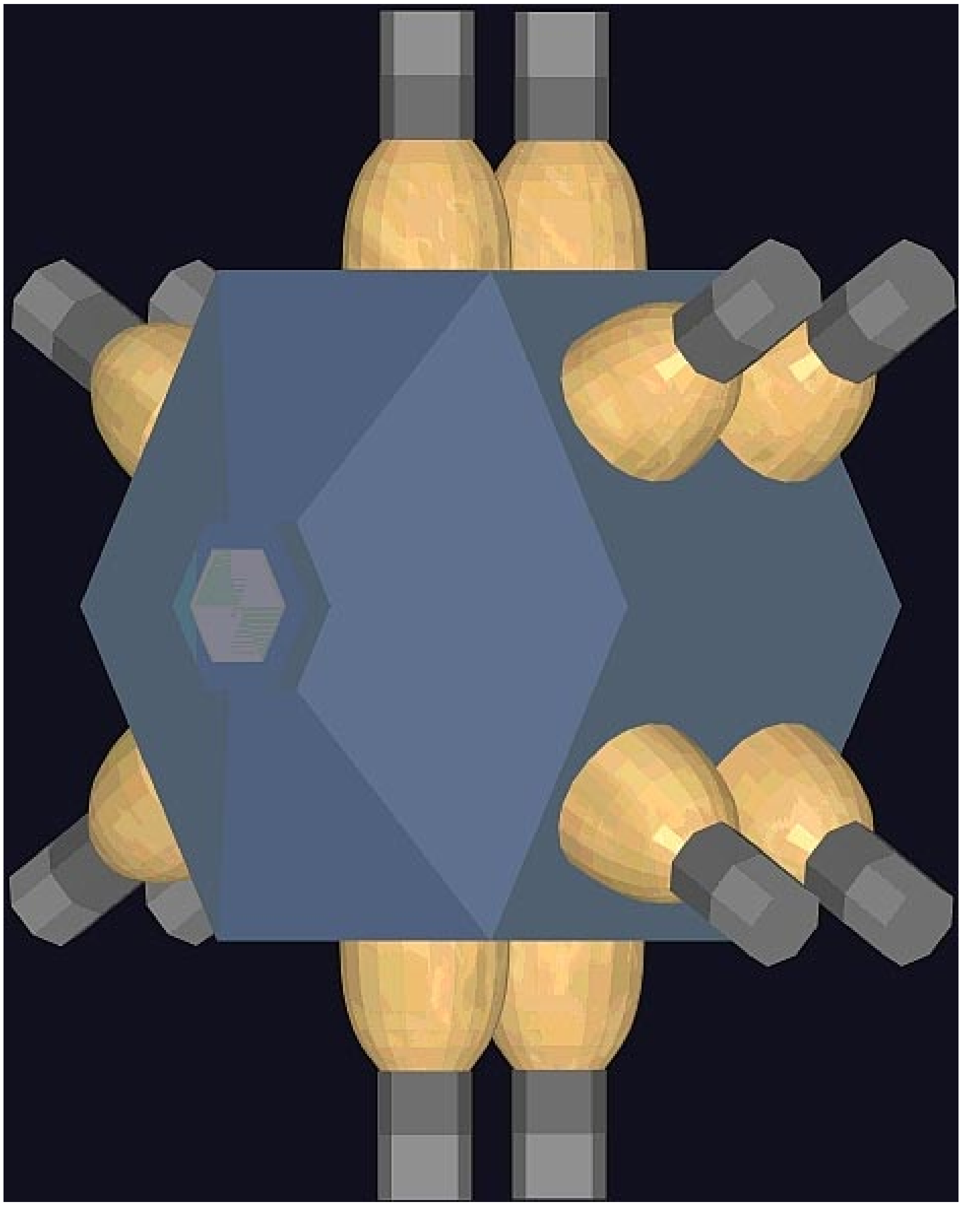
- 3 Tesla solenoid channel, (Bore = 30 cm)
- Particle ID rejects incoming pions and electrons
- Two momentum measure−ments: Bent solenoid spectrometer + precision time−of−flight
- TPC: Position & Direction
- Fast cherenkov timing counter −> arrival time

Particle Identification

Univ. of Mississippi

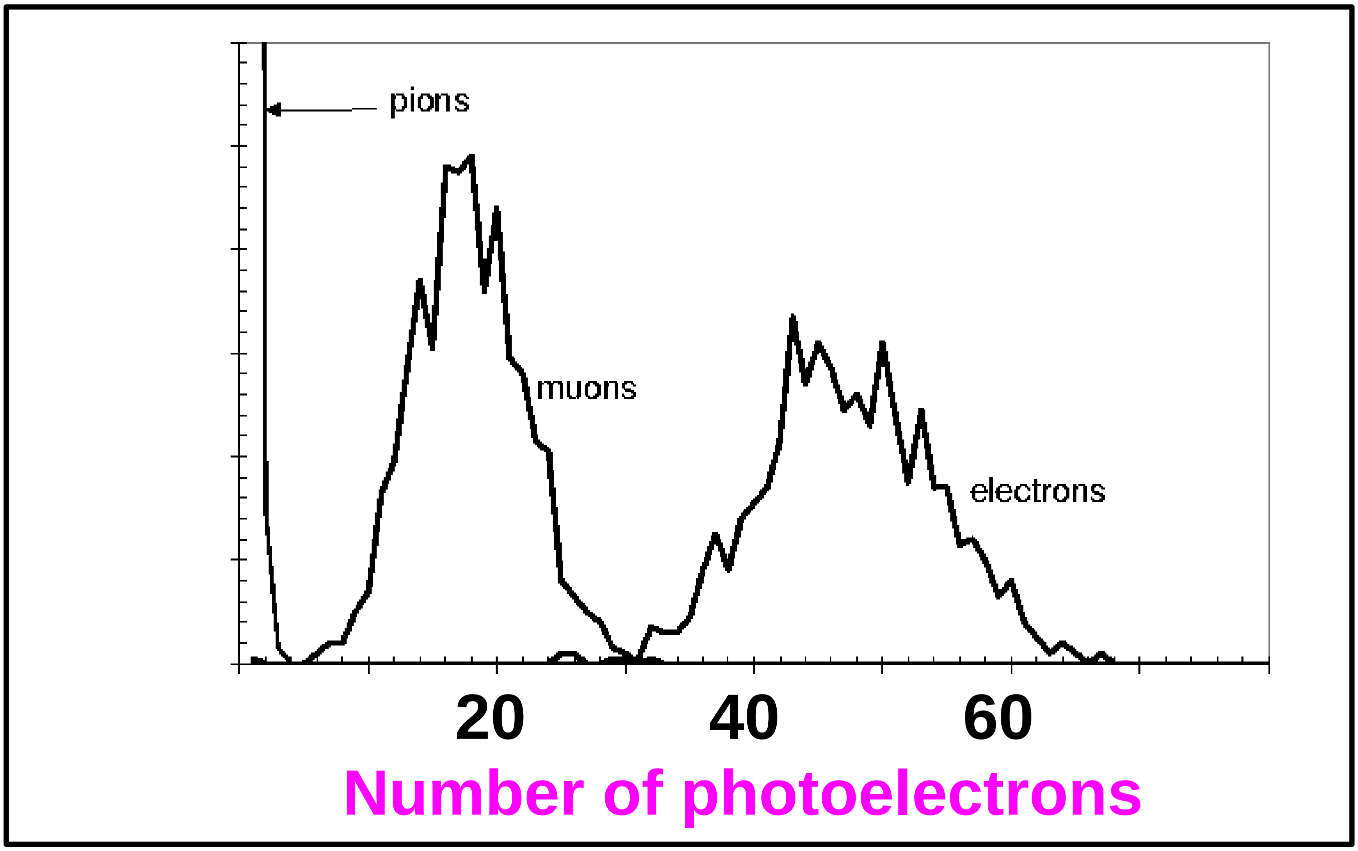
- **Need to reject incoming pions and electrons.**
- **Appropriate threshold cherenkov devices being prototyped.**

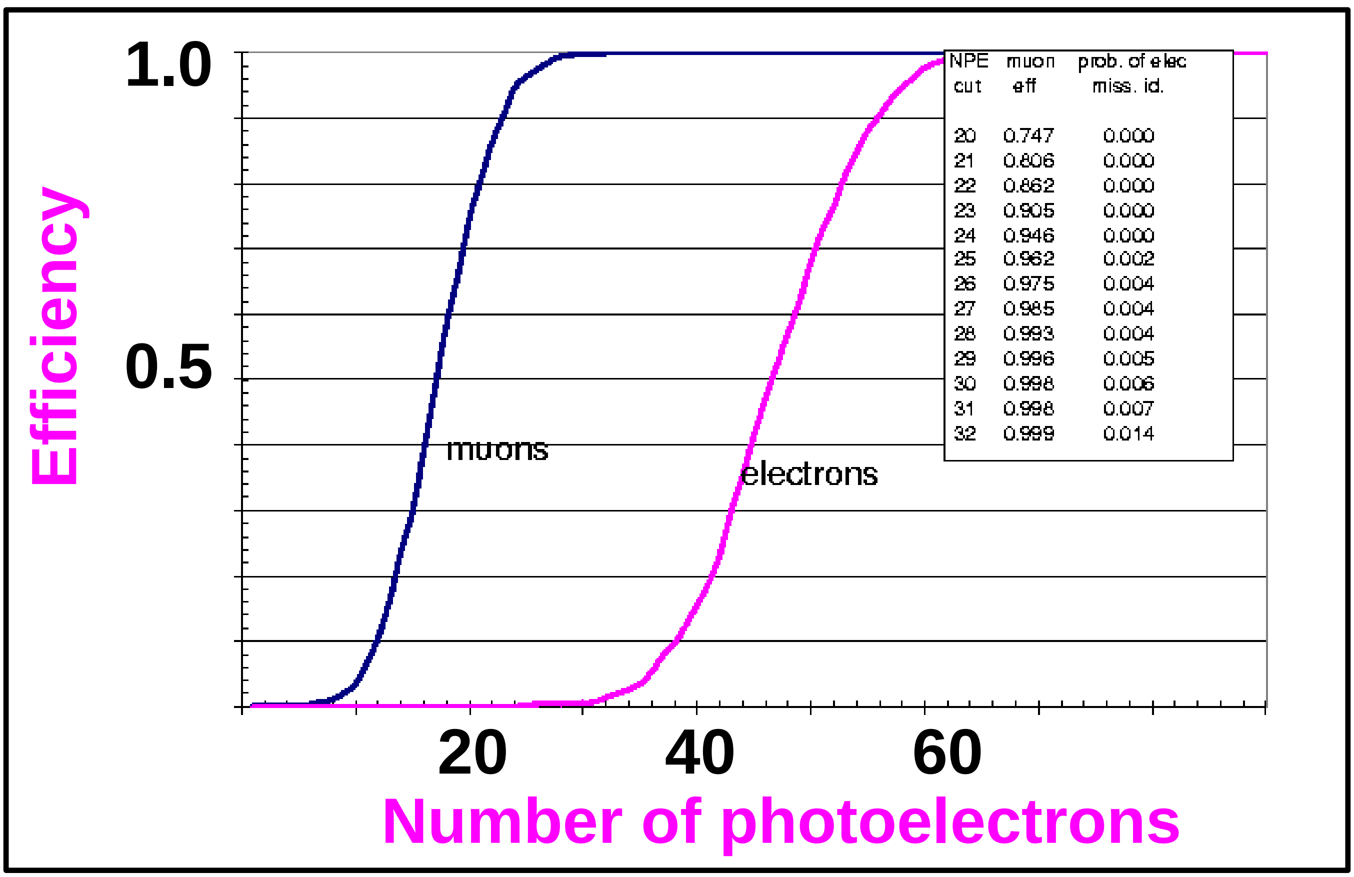




p_{beam} = 186 MeV/c
n = 1.244
$p_{min}(e)$ = 0.007 MeV/c, $\Theta_c(e) = 36^o$
$p_{min}(\mu)$ = 143 MeV/c, $\Theta_c(\mu) = 22^o$
$p_{min}(\pi)$ = 187 MeV/c

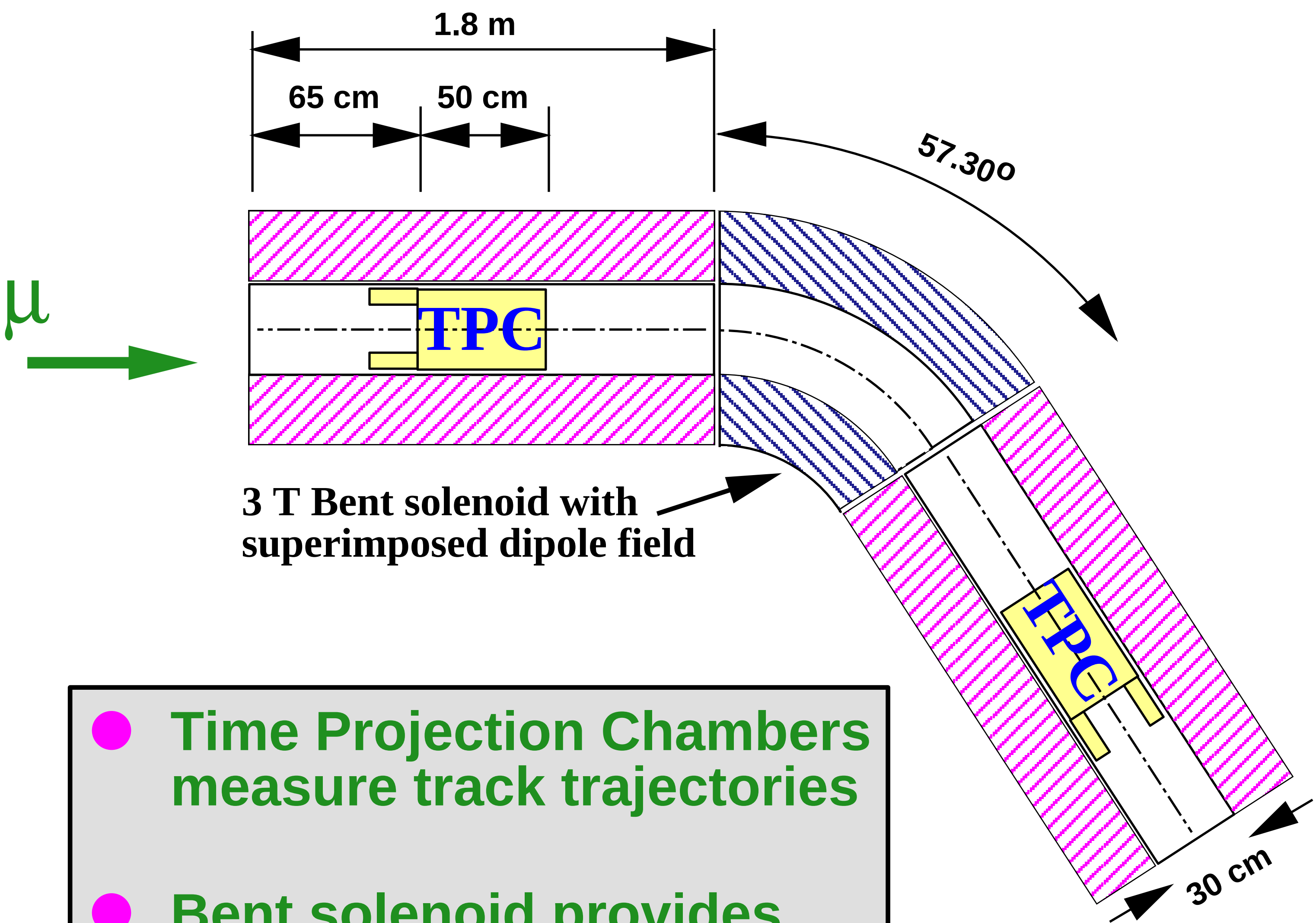
Preliminary Cherenkov Particle ID Simulation Results: fc−72 Cv radiator





NPE cut	muon eff	prob. of elec miss. id.
20	0.747	0.000
21	0.806	0.000
22	0.862	0.000
23	0.905	0.000
24	0.946	0.000
25	0.962	0.002
26	0.975	0.004
27	0.985	0.004
28	0.993	0.004
29	0.996	0.005
30	0.998	0.006
31	0.998	0.007
32	0.999	0.014

Momentum Spectrometer



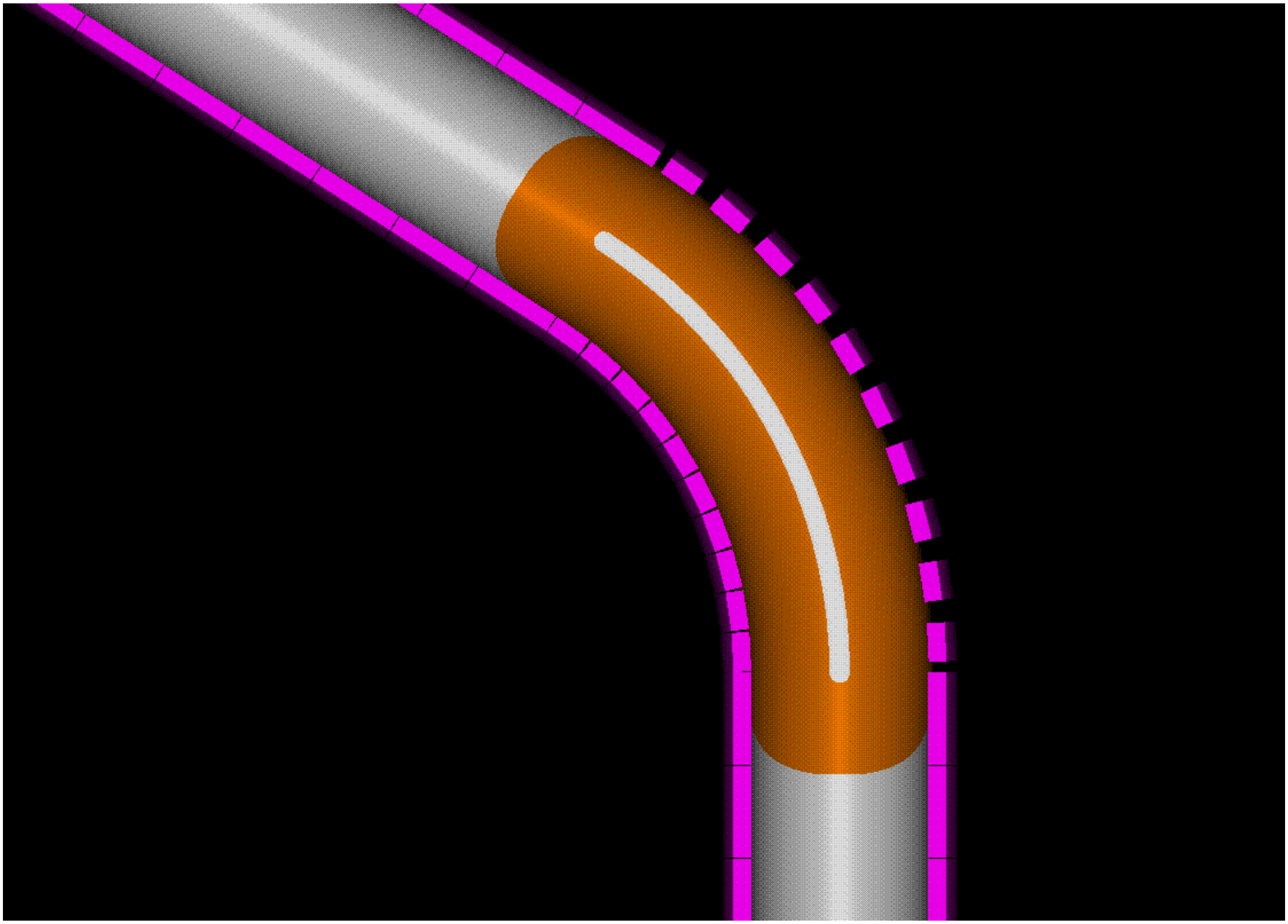
- Time Projection Chambers measure track trajectories
- Bent solenoid provides dispersion

Bent Solenoid Design

National High Magnetic Field Lab, FSU

- **Conceptual design study of magnet systems for 3T instrumentation channel.**
  - ☛ **Geometry & positions of conductors.**
  - ☛ **Current densities, conductor type**
  - ☛ **Field quality**
  - ☛ **Approximate cost estimate**

	Solenoids	Dipole
Max. B at windings	> 3.0 T	~3.6 T
Operating current	1174 A	1903 A
Conductor type	Rutherford	rect. monolith
Cu:NbTi ratio	4:1	4:1
Stored energy	1.8 MJ	25 kJ
Conductor length	18.9 km	0.6 km
Conductor mass	1130 kg	40 kg
Conductor cost	216 k$	4 k$

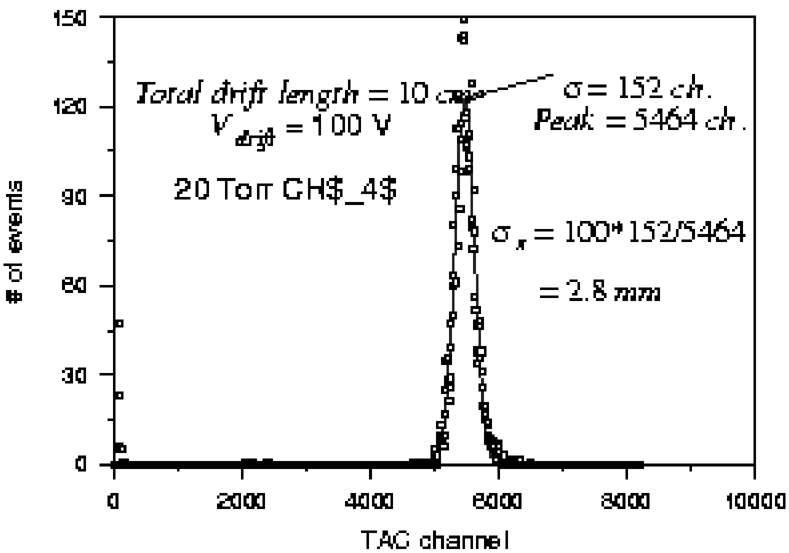


Low Pressure TPCs

Princeton

- Multiple scattering too large in gas at atmos−pheric pressure −> low pressure tracker.

- Prototype low pressure TPC constructed & tested at Princeton.



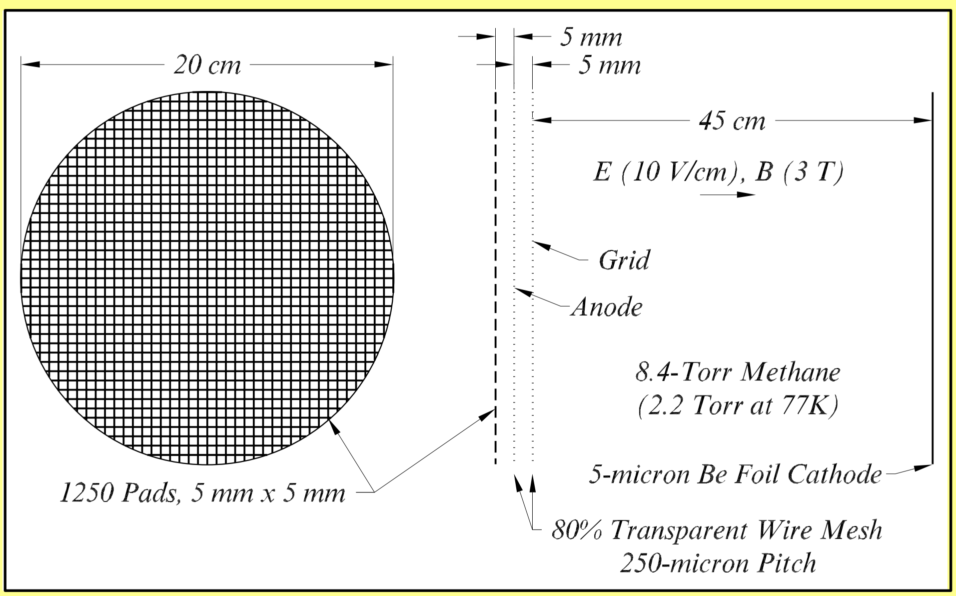
- Longitudinal diffusion measured over 10 cm drift with methane, ethane, isobutane, & CO_2 −> slightly better than expected.

- Drift velocity also measured, and agrees with expectations.

Next Low Pressure TPC steps :

- **Measure transverse diffusion ... needs several readout channels instrumented.**

- **Build a full scale prototype and measure its performance in an appropriate magnetic field (e.g. at Lab G).**



15 points per track segment

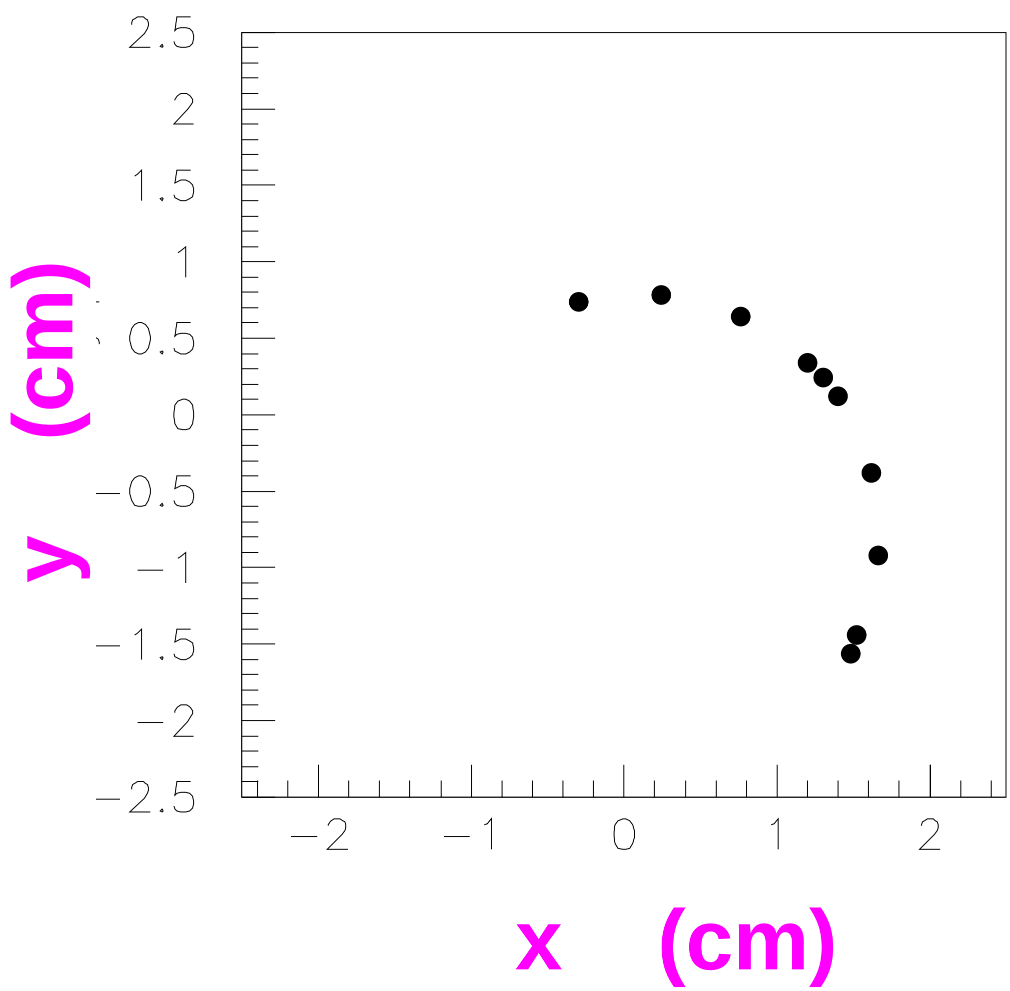
$\sigma_p/p \sim 0.0014$ at 165 MeV/c

$\sigma_\theta \sim 1$ mrad

GEANT Simulation Results

Steve Kahn (BNL)

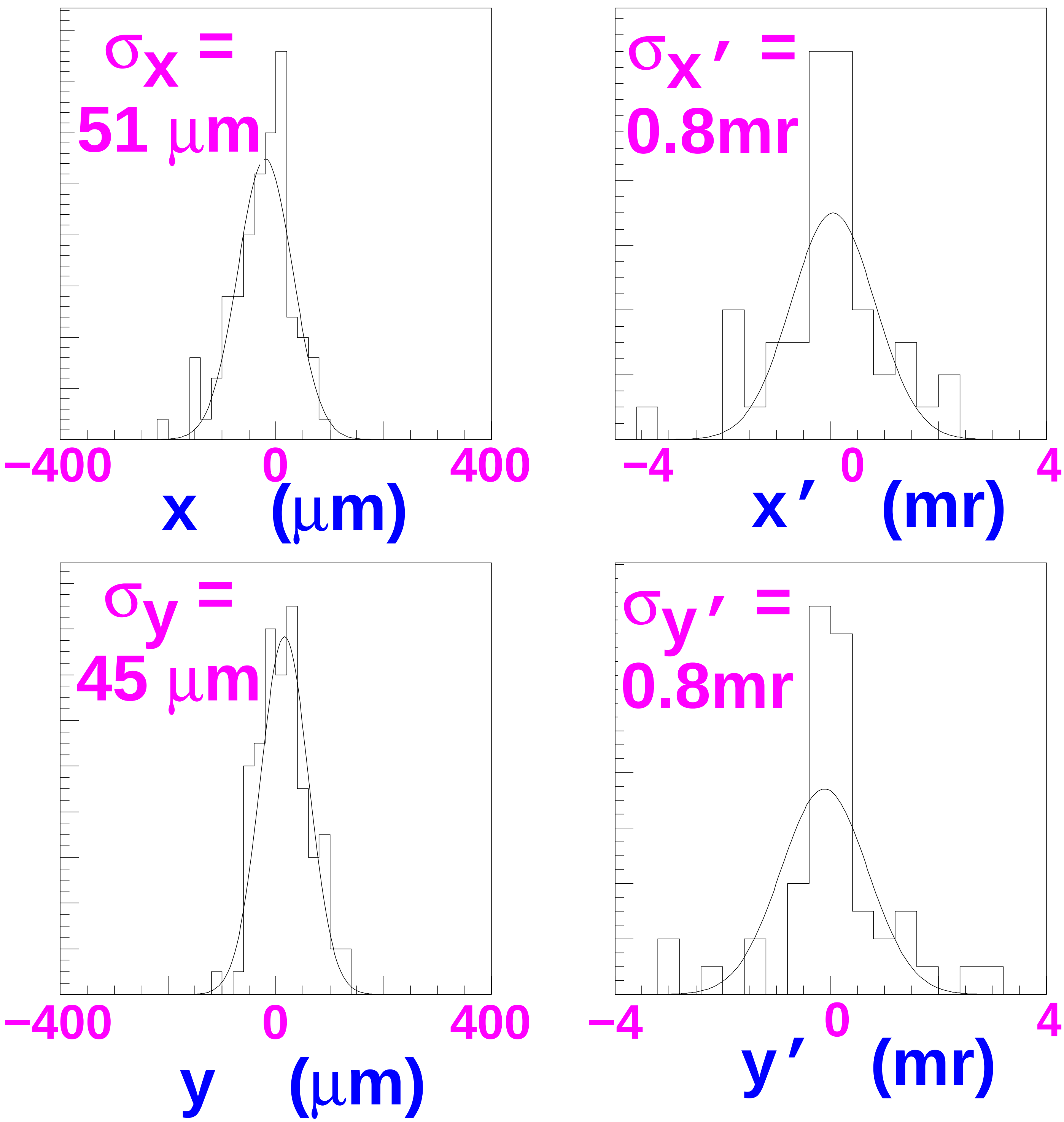
Simulation includes tracking through field, scattering, straggling, TPC resolutions vs drift distance, & track−reconstruction.



GEANT Simulation Results

Steve Kahn (BNL)

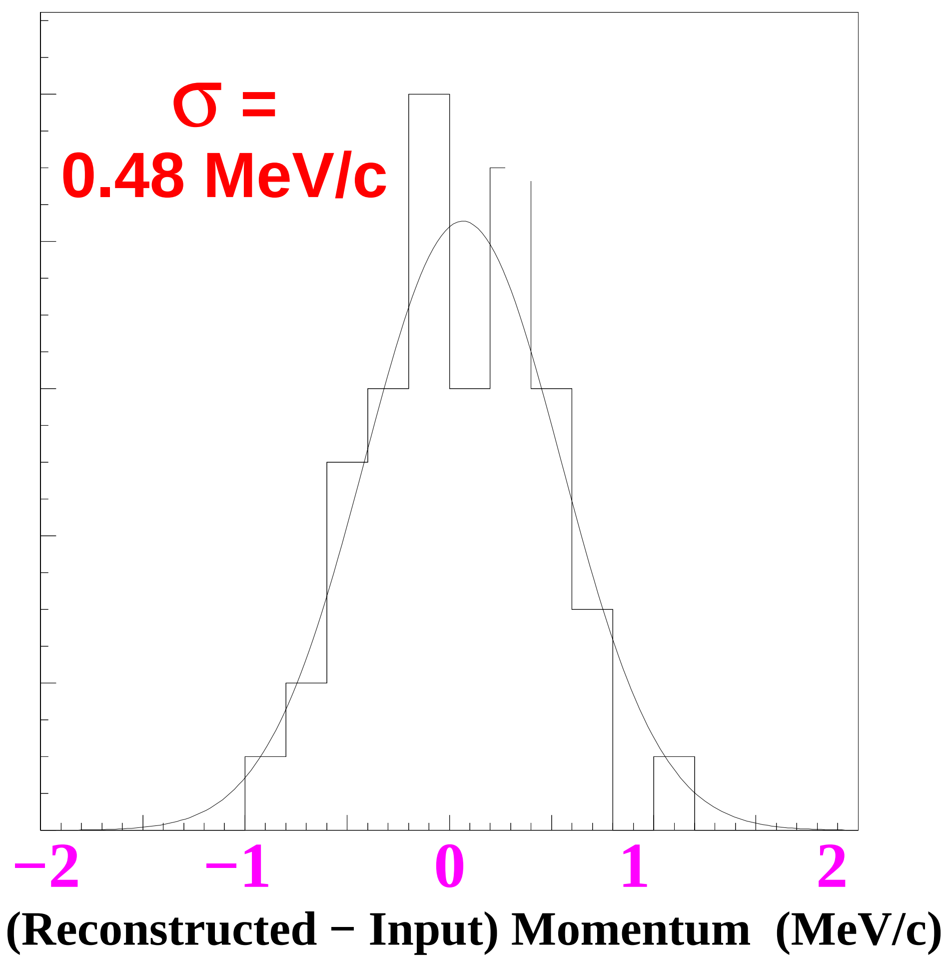
Position and Angular Resolutions



GEANT Simulation Results

Steve Kahn (BNL)

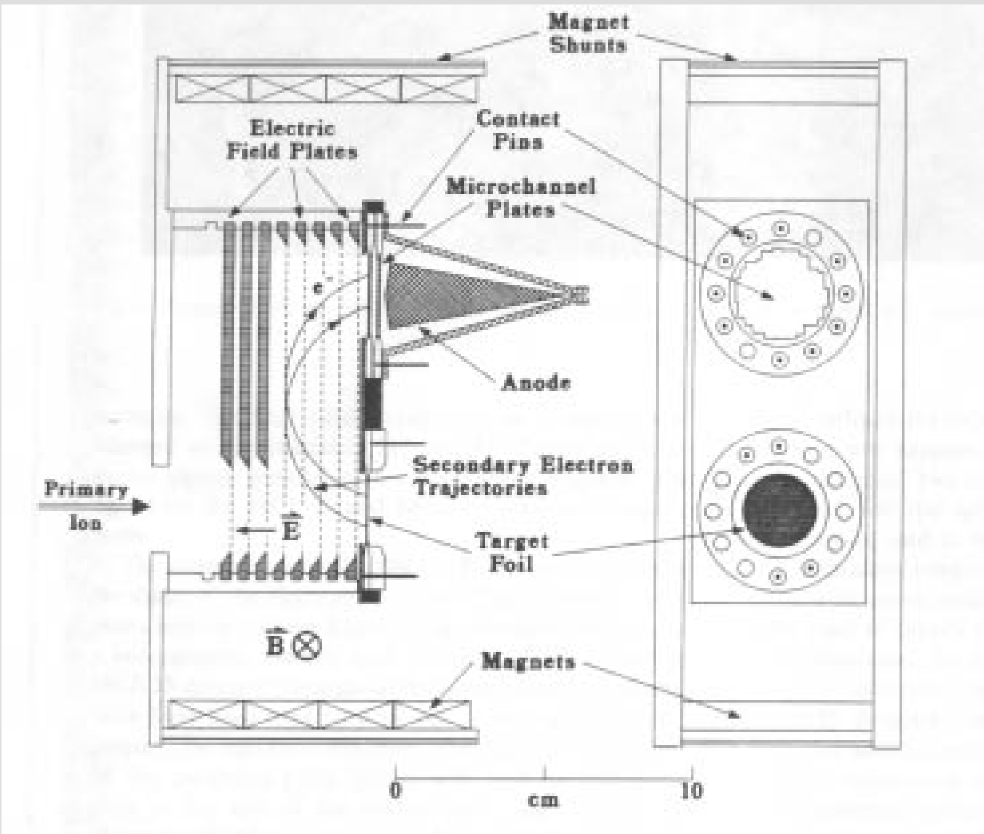
Momentum Resolution



Time−of−Arrival Measurement

FNAL, Princeton, UCLA

- **For the channel to work properly, particles must arrive in a small part (5%) of the rf cycle (−> ~ 60 ps).**
- **Best relevant σ_t achieved so far in a particle detector :**



Krauss et al.
NIM A264 (1988) 327

Microchannel plate amplifi−cation

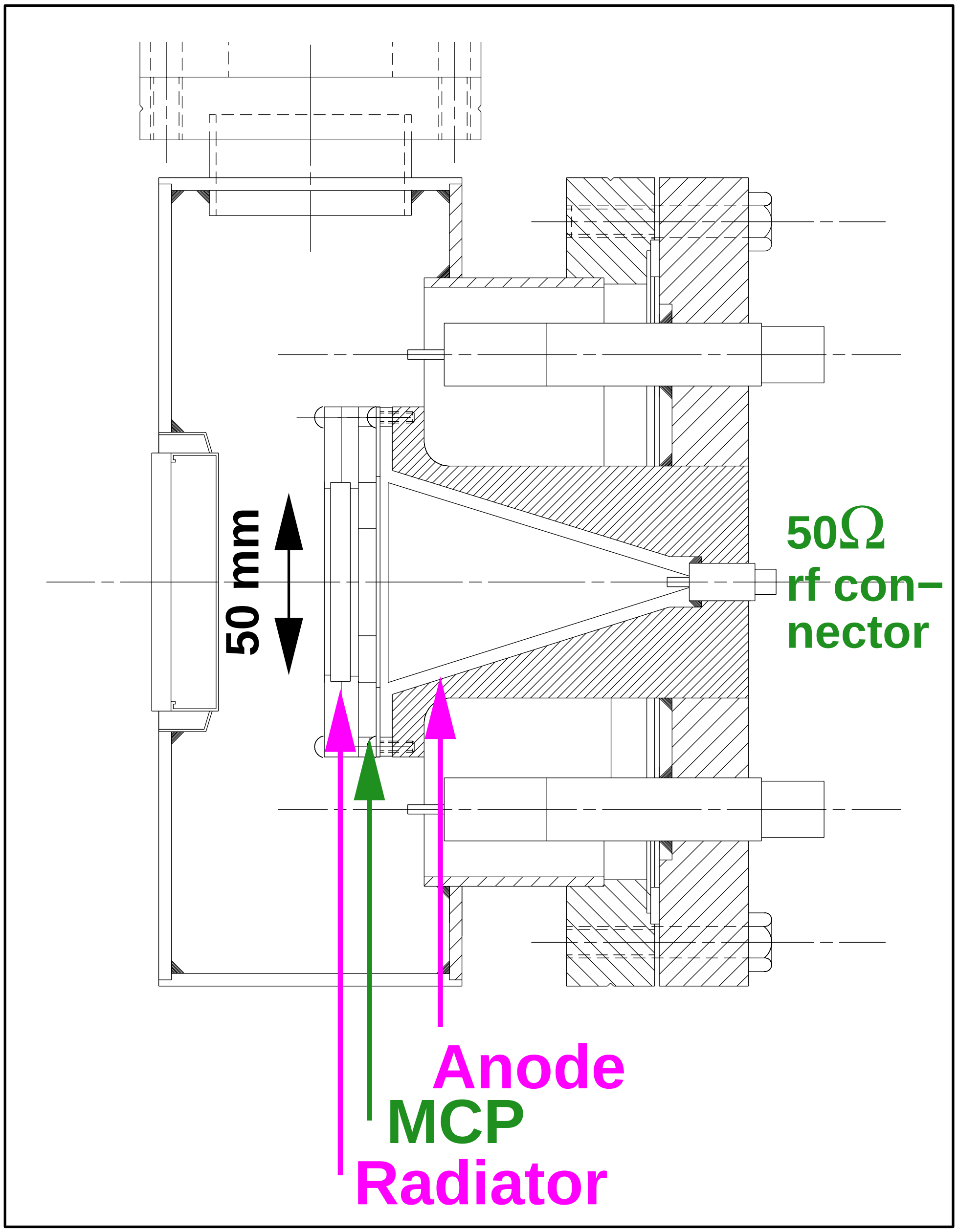
σ_t ~ 50 ps

- **With a cherenkov radiator & improved electron optics believe we can get to σ_t ~ 30 ps −> adequate to select particles within Δt ~ 60 ps.**
- **Operation of Microchannel plate in 2T field believed to be OK .... but operation in a 3T fields needs to be demonstrated with a modern (small pore size) MCP. Plan to test this at Lab G in the Fall (need some designer help).**

FAST TIMING R&D

FNAL, Princeton, UCLA

- **Develop a fast timing device using a MgF_2 Cherenkov radiator, CsI photocathode, state−of−the−art microchannel plate multiplier, RF output connectors −> σ_t = 10 − 20 ps.**



Overall mech−anical design complete (detail−ing to be done)

Output anode design under−stood

MCP with 18 mm small pore pixels exists

Radiator + photocathode + MCP + anode + rf connector test being prepared.

Time−of−Flight System

- **Note: For p = 187 MeV/c, $\gamma\beta c\tau$ ~ 1 km ... so a fraction of 1% of the muons will decay whilst traversing the instrumentation channel.**

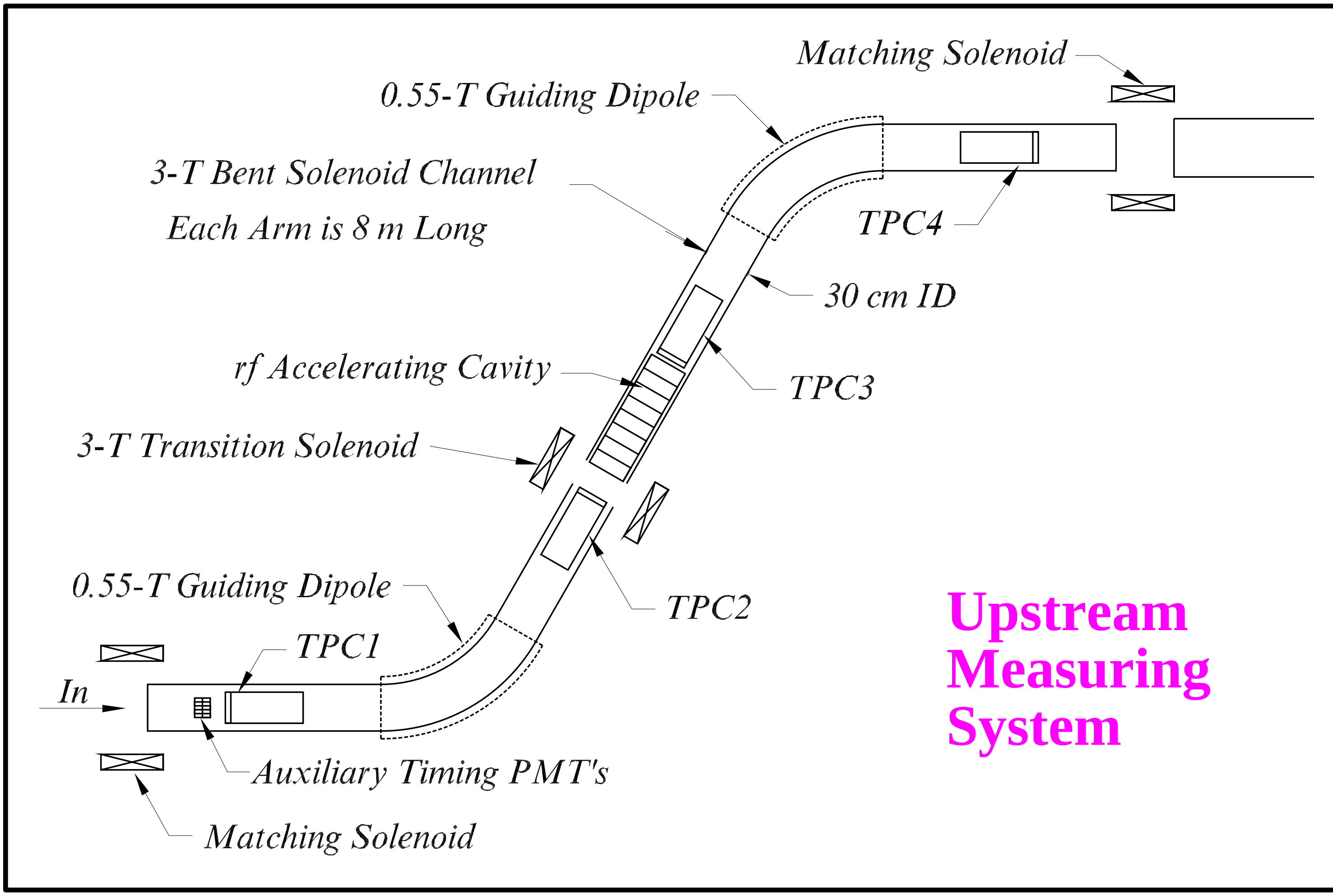
- **Employ a TOF system to reject muons that decay within the instrumentation channel :**

ToF Differences (ns) over 3m path

	p (MeV/c)				
	100	187	200	260	300
$\mu - e$	4.5	1.5	1.3	0.80	0.60
$\pi - \mu$	2.6	1.0	0.9	0.56	0.43

- **Will also yield additional rejection against incoming pions.**

Time Measurement − Backup Solution



- **Auxiliary timing device**

- **TPC 1 −> helix before first bend**
- **Bent Solenoid**
- **TPC 2 −> helix after first bend**

First Momentum Measurment

- **rf accelerating cavity**

rf

- **TPC 3 −> helix before second bend**
- **Bent Solenoid**
- **TPC 4 −> helix after second bend**

Second Momentum Measurment

GEANT Simulation of Beam Measurements

- GEANT simulation of 10000 beam particles passing through one & five 1.5 m (15 Tesla) cooling sections.

- The distributions are smeared by the resolution functions of the MUCOOL instrumentation -> predictions for measurement precision.

	ε_T (π mm−mr) Input	Output	$(\varepsilon_{in}-\varepsilon_{out})/\varepsilon_{in}$
1 Section	1520	1470	0.034
5 Sections	1520	1120	0.263

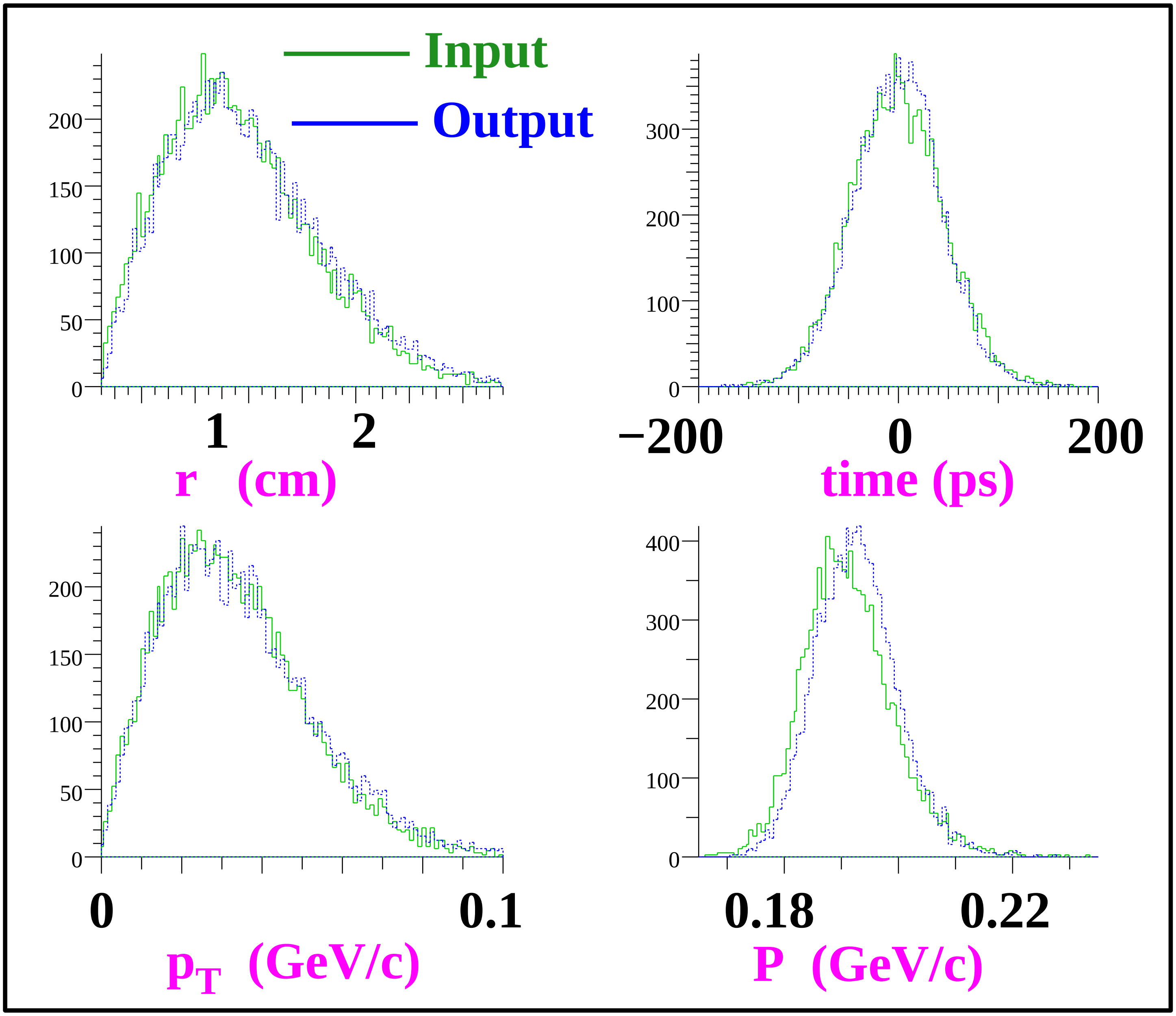
*) With 10^5 muons recorded, $\sigma_\varepsilon/\varepsilon = 0.003$.

- A successful outcome of the measurements would be to achieve these "emittance" reductions and demonstrate that with our cooling simulations we can predict how the particle distributions at the output depend on there input positions in 6−D phase−space, and variations in the channel parameters.

GEANT Simulation of Beam Measurements − 1

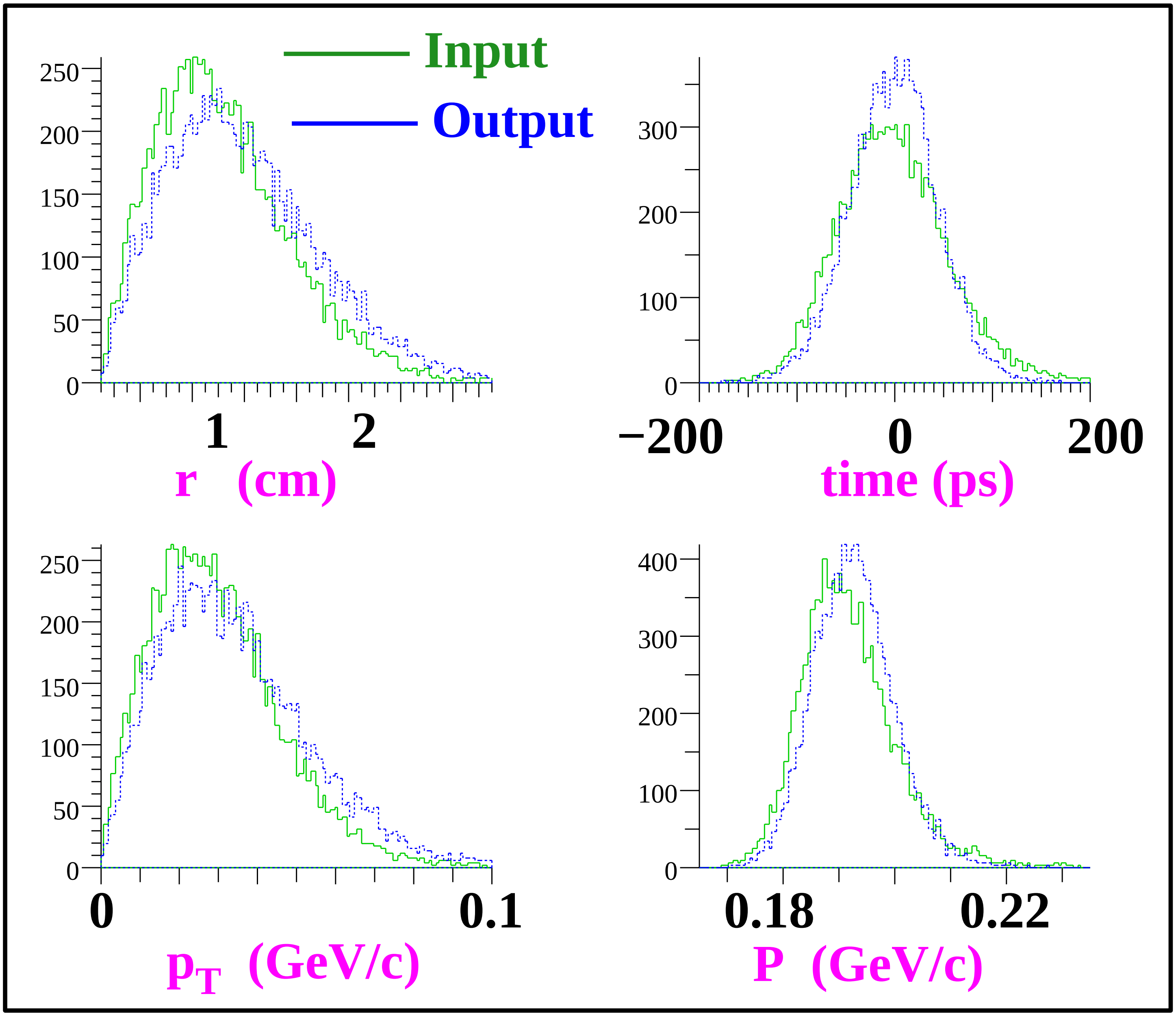
- GEANT simulation of beam passing through one 1.5 m (15 Tesla) cooling section.

- The distributions are smeared by the resolution functions of the MUCOOL instrumentation.



GEANT Simulation of Beam Measurements − 2

- GEANT simulation of beam passing through five 1.5 m (15 Tesla) cooling section.
- The distributions are smeared by the resolution functions of the MUCOOL instrumentation.

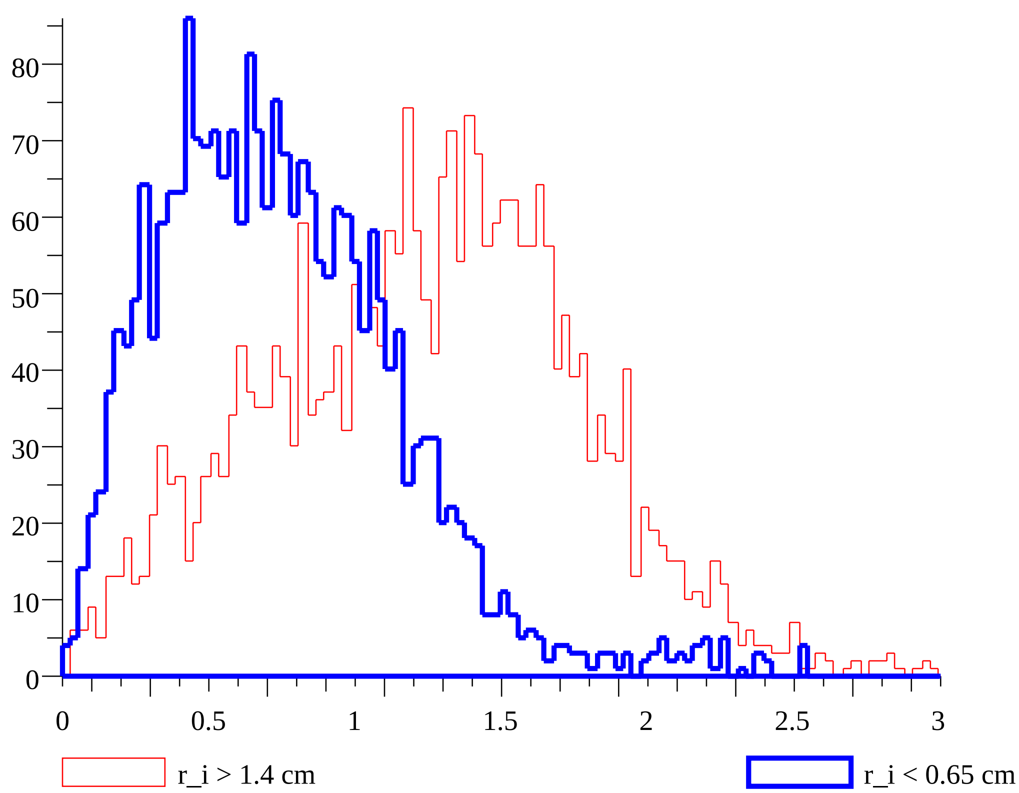


GEANT Simulation of Beam Measurements − 3

- The power of the single particle experiment is that it will enable correlations between the input and output particle positions to be measured in great detail.

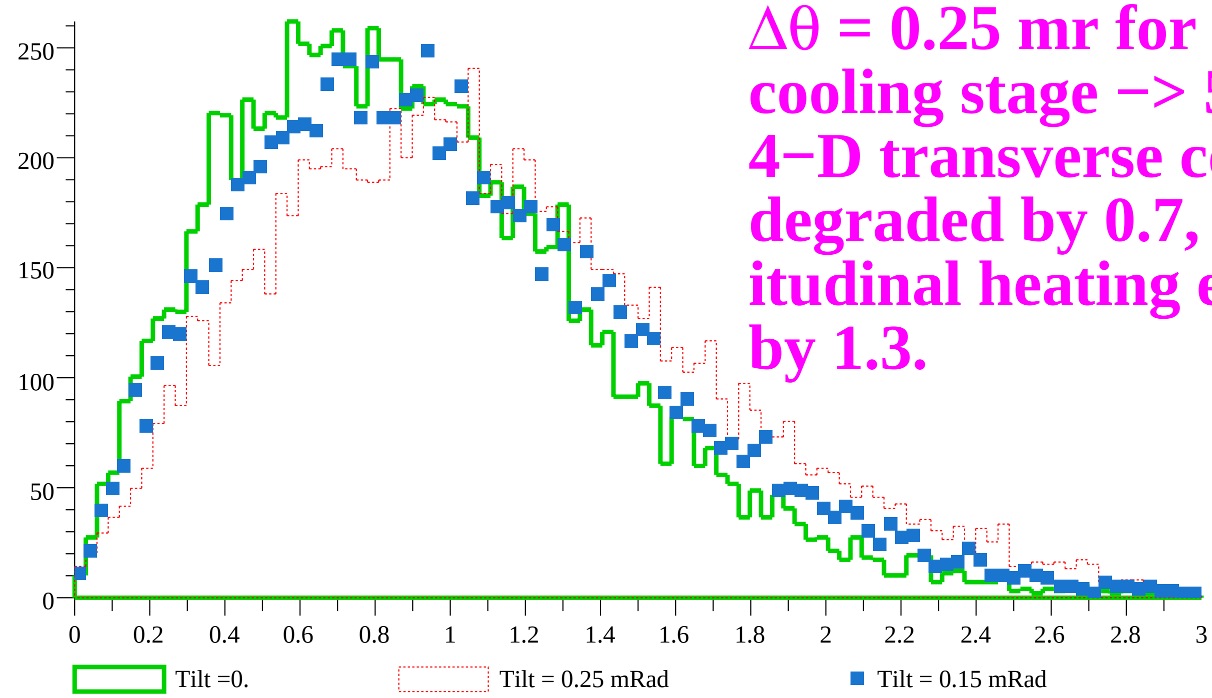
- GEANT simulation of the measured population for 10000 muons at the end of five 1.5 m (15 Tesla) cooling sections:

EXAMPLE: Output radial distributions for muons at small and large input radii:

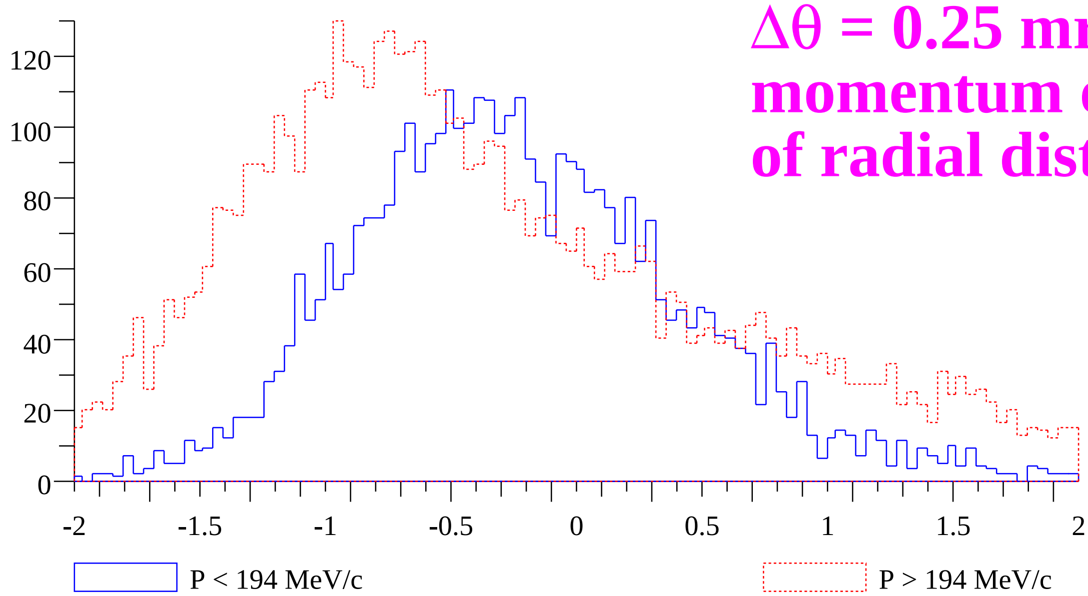


GEANT Simulation of Beam Measurements − 4

- **To illustrate the need for this level of diagnostics, imagine that, in a 5−section system, there is a small misalignment of one of the coils within the second 15T solenoid −> transverse heating.**



Δθ = 0.25 mr for complete cooling stage −> 5% loss, 4−D transverse cooling degraded by 0.7, & long−itudinal heating enhanced by 1.3.



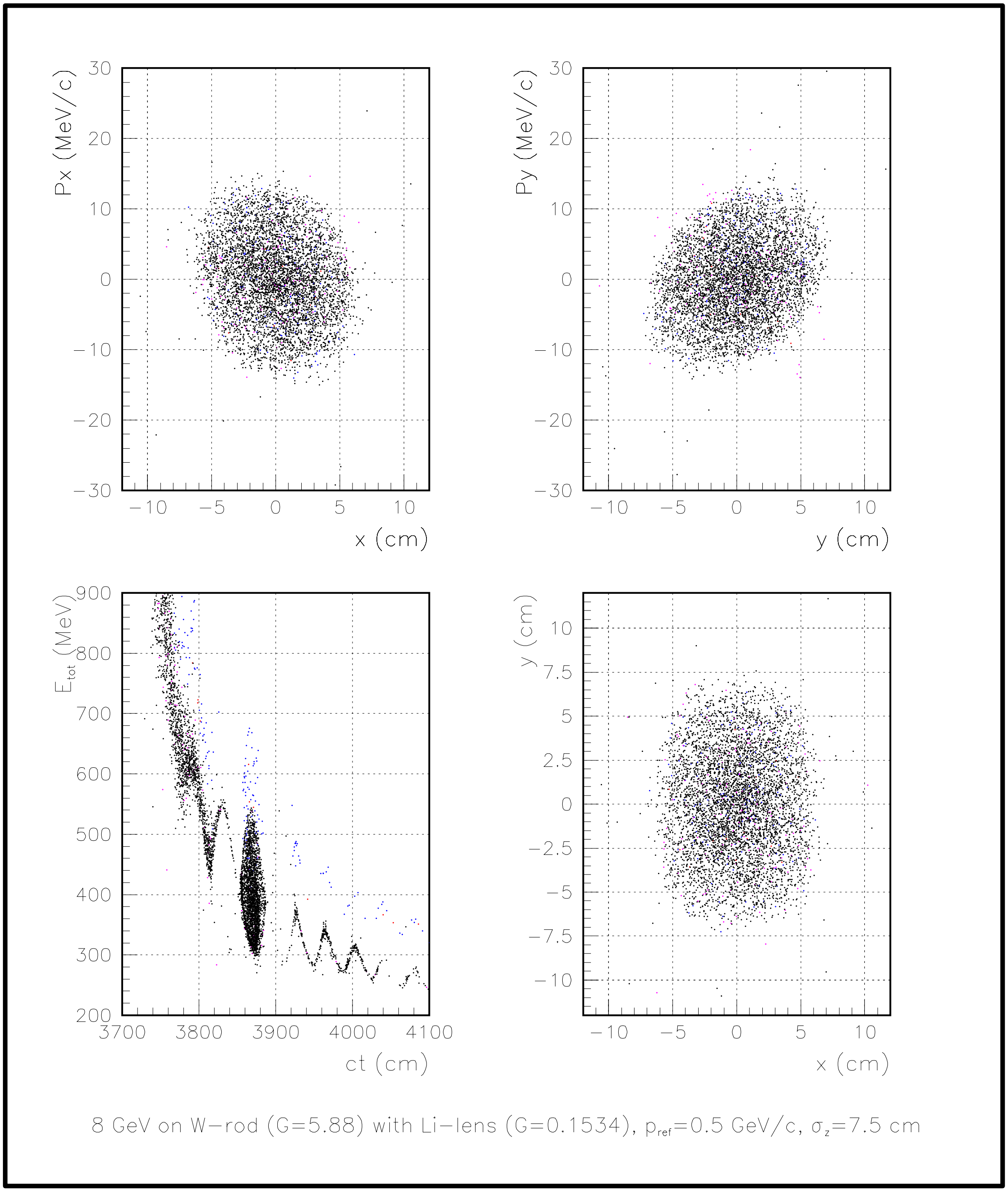
Δθ = 0.25 mr −> momentum dependence of radial distribution

Beamline Location & Bunched Beam Option

- **We believe we need the full diagnostic capability of a single−particle experiment.**
- **Assuming success ... we do not yet have a plan for the longer term R&D .... but the location of the single−particle experiment and the design of the associated beamline can open or close possible future options.**
- **With this in mind, there has been an initial study exploring the possibility of creating a bunched muon beam at the Booster. The challenge is to produce "clean" muon bunches.**
- **To finish the muon beamline design studies we will need continued/further support from the beamline design experts at Fermilab. We would like sufficient support to have a beamline design report completed in the near future.**

Bunched beam study results

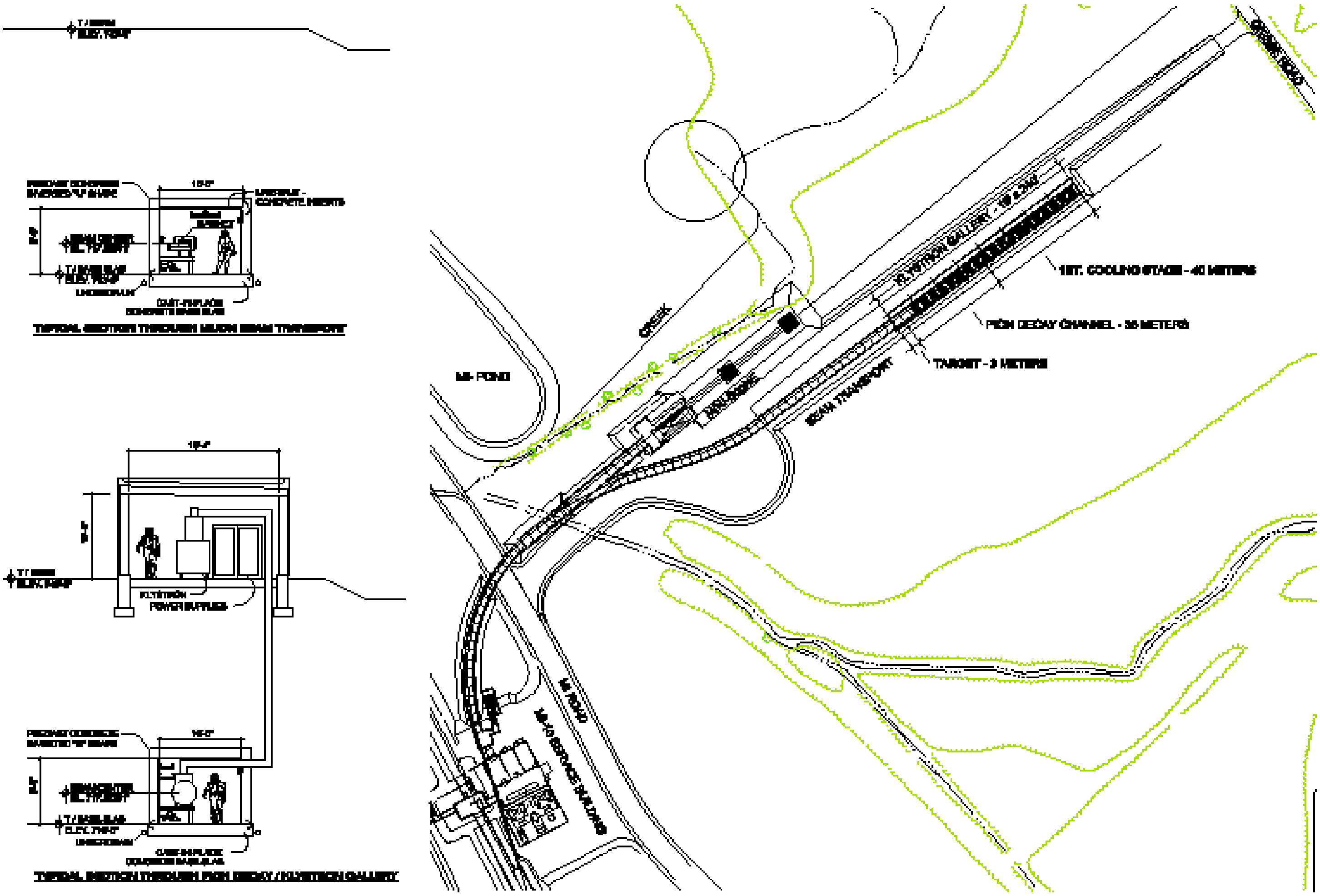
V. Balbakov, N. Holtkamp, N. Mokhov



- 2.5×10^{-3} muons/proton. With 2×10^{10} protons/bunch –> 5×10^{7} muons/bunch

Booster Beamline Layout

MUON COOLING EXPERIMENT



- **Still to be done :**

  Understand how to clean the beam

  Understand how to exploit a bunched beam

MUCOOL University Activities

We expect to involve more university groups in MUCOOL. So far, on the very active list are:

IIT : Liquid Hydrogen Absorber Design:

Requires GEANT cooling simulation studies, plus engineering design. Hopefully will lead to construction of liquid hydrogen absorber at IIT, and beam tests.

Mississippi : RF Cavity Studies, Particle ID Detector Design for Cooling Instrumentation, Cooling simulation studies:

Machining of Copper Test Cavity, measurement of resistivity of Beryllium foils at Liquid Nitrogen temperatures, design of a cherenkov counter for $\mu-\pi$ and $\mu-e$ separation at 100−300 MeV. GEANT simulations of cooling channel.

UCLA : Fast Timing R&D:

Design & prototype measurements of a ~100ps timing device for the MUCOOL instrumentation. R&D studies for a super−fast (10ps) timing device.

Princeton : Low Pressure TPC:

Design & prototype measurements of a low pressure TPC for the MUCOOL instrumentation.

Illinois University Consortium

- IIT led consortium

IIT: D.M. Kaplan, L.M. Lederman, T.I. Morrison

Chicago: H.−J. Kim, Y.W. Wah

Northern Illinois: G. Blazey, D. Hedin

Northwestern: H. Schellman

- Proposal to state of Illinois, June 1999, for $600K has been funded.
- Will support research staff hires to work on aspects of MUCOOL.
- Expect to submit a renewal proposal for ~$2M/yr by end of 1999.

Summary

- Muon cooling R&D is on the critical path for determining the feasibility of a muon collider.
- The MUCOOL Collaboration received its first hardware funding 1 year ago. With this we have launched the following R&D:

  RF cavities with high accelerating gradients

  An alternating solenoid transverse cooling test channel.

  Liquid Lithium Lenses

  Beam−test facility & experiment design.

- These hardware activities have been crucial in guiding the cooling simulation design studies −> realistic rf parameters, coil geometries, etc.
- We may have to choose between this R&D program focussed on the feasibility of a muon collider, & a modified R&D program focussed on a neutrino source .... this needs clarification !
- Completion of the muon beamline design studies is a high priority for the design of a beam test experiment. The most attractive location currently appears to be at the Booster.
- We propose to pursue a single particle experiment which will enable performance of the initial cooling prototype hardware to do studies in detail.